DAHLGREN DIVISION
NAVAL SURFACE WARFARE CENTER
Dahlgren, Virginia 22448-5100

NSWCDD/TR-96/178

WATER BARRIER LINE CHARGE PLUME VIDEO ANALYSIS

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WEAPONS SYSTEMS DEPARTMENT

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13. ABSTRACT (*Maximum 200 words*)
The Naval Surface Warfare Center Dahlgren Division (NSWCDD) is developing technology for a concept that has the potential to be very effective in defending Navy platforms against high-speed, sea-skimming, antiship cruise missiles (ASCMs). This concept uses a new kill mechanism, a wall of water, to provide a low cost, universal terminal defense system for Navy ships. This wall of water or water barrier is formed from the shallow detonation of multiple underwater explosive charges. To support the development and evaluation of the Water Barrier Concept, underwater detonation tests of scaled line charges were conducted in July 1995 to determine the amount of water ejected into the air by the subsurface detonation of continuous and discrete line charges. The above-surface plumes were generated by the underwater detonation of Composition C-4 demolition blocks that were configured into continuous line charges that were 30 to 56 feet in length. Plumes also were produced from the sequential underwater detonation of discrete line charges that consisted of five to eight 10-pound charges separated by 8 feet and fabricated from C-4 demolition blocks. Line charge depths and horizontal separation of discrete charges were chosen to maximize the amount of water ejected into the air. The plumes were photographed with 30-picture-per-second super VHS video cameras placed parallel and normal to the charge line. Dimensions of the plumes produced by the test shots were determined from digitized images captured from the video tapes. This report presents the results from the measurement of the plume heights and plume profiles produced by the underwater detonation of continuous and discrete line charges in this series of test shots.

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FOREWORD

Under the sponsorship of Mr. Dave Siegel, Code 351, Office of Naval Research (ONR), the Naval Surface Warfare Center Dahlgren Division (NSWCDD) is developing technology that uses a new kill mechanism, a wall of water, to provide a low-cost, effective terminal defense of Navy ships against high-speed, sea-skimming antiship cruise missiles (ASCMs). The Water Barrier Ship Self-Defense generates a wall of water from the shallow detonations of multiple underwater explosive charges. This wall of water will prevent target debris and warhead fragments produced at very short range from causing significant damage to own ship. Furthermore, the barrier will defeat the fuzing and structure of ASCM sea skimmers that have penetrated the self-defense layer.

To evaluate the water barrier concept for ship self-defense, thirteen underwater detonation tests were fired during July 1995 in a water-filled quarry facility in Rustburg, VA, operated by Dynamic Testing, Incorporated, a subsidiary of NKF Engineering, Incorporated. This report presents the results from the measurement of the plume dimensions produced by the underwater detonation of continuous and discrete line charges in this series of test shots.

The Naval Surface Warfare Center test team included representatives of two Divisions. Microwave absorption measurement equipment was provided and operated by personnel from Code B44 of the Dahlgren Division. The following were involved: K. Boulais, J. Choe, and K. Erwin. The conductivity probe equipment was provided and operated by L. Lipton from Code 450 of the Indian Head Division. Video equipment was set up and operated by J. Connor of Code 9540, Indian Head Division, assisted by C. Higdon, Dahlgren Division, Code G23. Planning and arrangements were carried out by L. Lipton and J. Connor of the Indian Head Division with advice and direction from C. Higdon.

Approved by:

David Malyevac

DAVID S. MALYEVAC, Deputy Head
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INTRODUCTION

BACKGROUND

Under the sponsorship of the Office of Naval Research, the Naval Surface Warfare Center Dahlgren Division (NSWCDD) is developing technology for a concept that has the potential to be very effective in defending Navy platforms against high-speed, sea-skimming, antiship cruise missiles (ASCMs). This concept uses a new kill mechanism, a wall of water, to provide a low cost, universal terminal defense system for Navy ships. This wall of water or water barrier is formed from the shallow detonation of multiple underwater explosive charges. This concept can be employed to slow or stop debris and warhead fragments from missiles killed at very short range to preclude significant damage to own ship. Furthermore, the barrier would defeat the fuzing and structure of ASCM sea skimmers that have penetrated the self-defense layer. Close-in employment of the barrier concept would increase the engagement space of self-defense weapons and help reduce detection range requirements.[1]

To support the development and evaluation of the Water Barrier Concept, underwater detonation tests of scaled line charges were conducted during July 1995 in a 130-foot-deep water-filled quarry operated by Dynamic Testing, Incorporated, in Rustburg, Virginia. The purpose of these tests was to determine the amount and density of water ejected into the air by the subsurface detonation of continuous and discrete line charges. The above-surface plumes were generated by the underwater detonation of Composition C-4 demolition blocks that were configured into continuous line charges that were 30 to 56 feet in length. Plumes also were produced from the sequential underwater detonation of discrete line charges that consisted of five to eight 10-pound charges separated by 8 feet and fabricated from C-4 demolition blocks. Line charge depths and horizontal separation of discrete charges were chosen to maximize the amount of water ejected into the air.[2-5]

The plumes were photographed with 30-picture-per-second super VHS video cameras placed parallel and normal to the charge line. Dimensions of the plumes produced by the test shots were determined from digitized images captured from the video tapes. The lateral extent of the water plume at 11.5 and 25 feet above the water surface as well as its maximum height above the water surface were determined. These data will be used in conjunction with data obtained from microwave absorption and electrical conductivity measurements made on the same plumes to evaluate the defensive capabilities of the water barrier as well as to verify a hydrodynamic computer model of plume generation from the shallow detonation of underwater explosives.[6] This report presents the results from the measurement of the plume heights and plume profiles produced by the underwater detonation of continuous and discrete line charges in this series of test shots.

EVOLUTION OF AN UNDERWATER EXPLOSION

An explosion is a chemical reaction in a substance which converts the original material into a gas at very high temperature and pressure. A reaction front—the detonation wave—propagates through the material at a velocity of several thousand meters per second. The detonation wave of an underwater explosion is transmitted into the surrounding water as a propagating shock front that travels radially outward toward the air/water interface above the detonation point. The wave reflects into the water as a rarefaction in order to conserve momentum and energy at the surface. Since water cannot sustain tension, a whitened area of cavitation is formed that rises from the surface. A shock is also propagated into the air but is far from the region above the explosion long before a water plume is formed.

The gas bubble, containing the gaseous explosion products, expands rapidly outward at a high velocity to relieve its high internal pressure. As the bubble rapidly expands, the bubble assumes a nearly spherical shape regardless of the initial charge shape. The water above the charge erupts upward - driven first by the reflected shock and later by the mass motion of the water pushed by the expanding bubble. For relatively shallow detonations, such as those fired for this test series, evolution from undisturbed surface to fully developed vertical plumes is complete in a few (~ 2) seconds. Somewhat more than 2 additional seconds are required for the water to subside to the surface.

Surface phenomena produced by detonation of spherical charge are described and discussed in the classic underwater explosion treatise by Cole.[7] In the following discussion the description is extended to include the phenomena observed above a linearly distributed line charge. Figures 1 and 2 display the line charge plume development just after a shallow detonation for a continuous line charge and a discrete line charge, respectively.

Spray Dome

The first visible event at the surface above the explosion is the cavitation whitening of the water due to the reflected rarefaction. The cavitated layer is ejected vertically upward with a speed that satisfies mass and momentum conservation laws. The reflection process produces a dome of water droplets whose profile on the photographic and video tape images suggests the Gaussian bell curve.

Bubble Phenomena

For the scaled firing depths used for these tests, the explosion gas bubble arrives at the surface before the shock reflection process has run its course. The bubble rises inside the cavitated Gaussian-like dome, creating a hollow core that is isolated from the atmosphere. This core increases in volume until its internal pressure is somewhat less than ambient. At the detonation depths chosen for these tests, a rapidly rising jet is often seen rising above the top of the dome as the gases vent upward to the atmosphere. As internal pressure decreases, horizontal and vertical growth of the plume slows. The bubble collapses and its bottom surface rushes up into the hollow core and pushes through the walls of the plume. Radial plumes are generated that are visible on camera records.

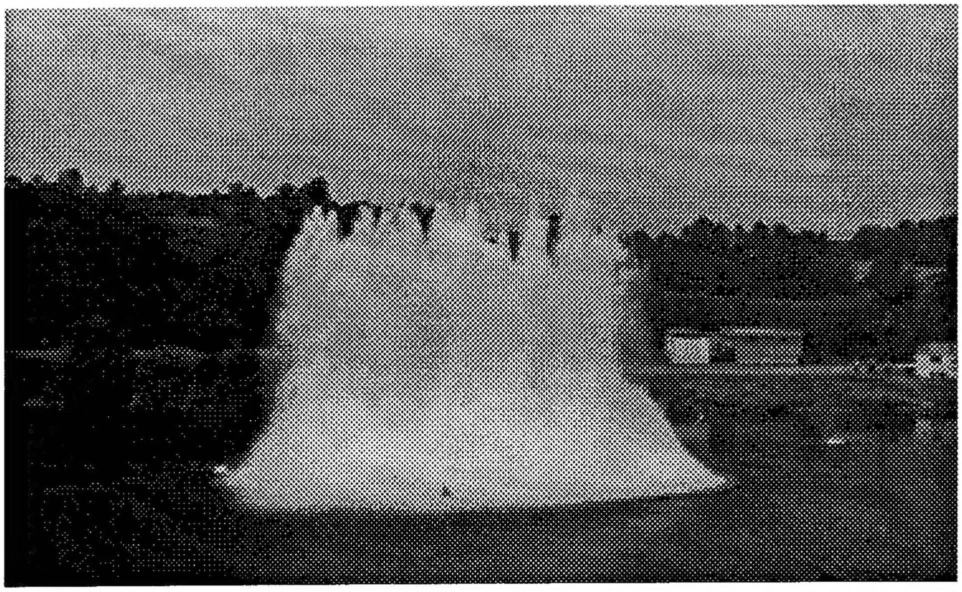

Figure 1. First Frame of Continuous Line Charge Plume Formation

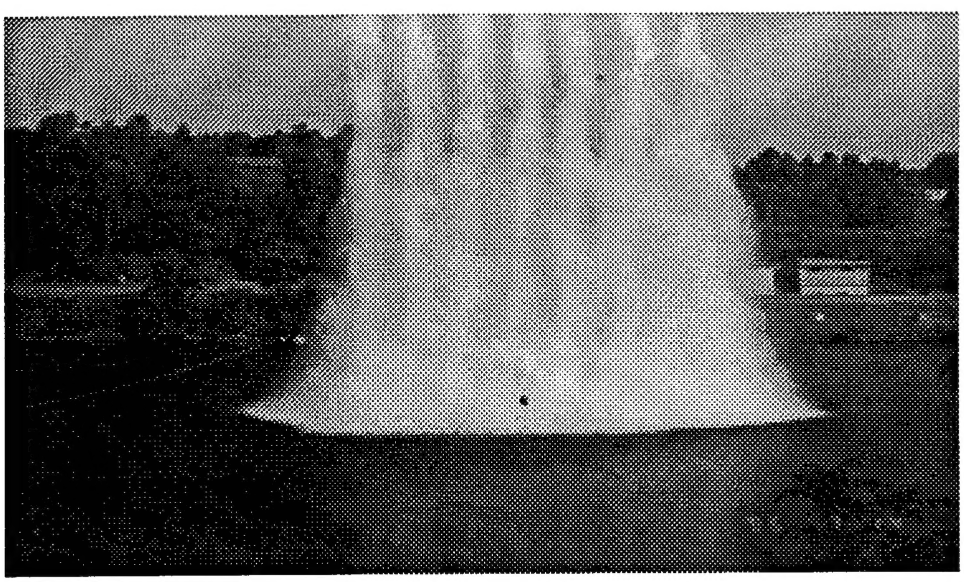

Figure 2. First Frame of Discrete Line Charge Plume Formation

Shockwave Interaction

When two or more discrete charges are detonated nearly simultaneously and close to one another at about the same shallow depth, each charge produces a nearly spherical shockwave. The shocks interact with one another at the water/air interface approximately midway between the charge support floats. A large impulse is delivered to the surface water between the charges; the water at these locations acquires large velocities exceeding those imparted to the cavitated water in the dome. Viewed from the side a vertical spike appears that moves ahead of the dome to significantly greater heights than the dome from detonation of a single charge. The horizontal component of velocity imparted to the surface water by the shock interaction pushes water ahead of the shock-produced dome. The consequent plume generated from the shallow detonation of multiple charges is wider than that produced by detonation of a single charge.

This surface interaction results in a pancake of water being added to the dome development. The plane of the pancake is vertical and normal to the axis of the line charge. It is the primary reason that a given amount of explosive should be distributed in discrete units rather than in a continuous line of the same linear density. Continuous charges produce domes without spikes induced by shock interactions.

TEST DETAILS

CHARGE CONFIGURATIONS

The line charges were constructed from 1.25-lb M113 Composition C-4 demolition blocks extended along a line at a relatively shallow firing depth. Each scaled charge was initiated from the surface end of 50-grain/foot detonating cord that ran from a surface float down to and along the line of C-4. A knot in the detonating cord was embedded in each C-4 charge to ensure detonation coupling.

The following two line charge configurations were examined:

- Continuous: Continuous line charges are illustrated in Figures 3 and 4. Single C-4 blocks were split lengthwise and fastened around a length of 1/4-inch steel rod along which the detonating cord also was fastened. The 10-inch-long blocks were placed end-to-end with 2-inch gaps between blocks. The rod was supported by several vertical lines suspended from balloon floats on the water surface. The floats were spaced 8 to 10 feet apart--sufficient to support the underwater charge at the desired depth along a horizontal line. The arrow denotes the direction from which the detonation begins.

- Discrete: Discrete line charges are illustrated in Figures 5, 6, 7, and 8. Separate charges, each weighing 10 lb, were fabricated on site from eight 1.25-lb demolition blocks. They were suspended from surface floats at horizontal separations approximating the firing depth. Detonating cord was strung from the surface down to and along the string of charges so that the time interval between detonations was determined by the detonation velocity in the detonating cord. This time interval is a few hundred microseconds.

The following two parameters have been used to characterize the tests:

- Charge weight per unit length: For a continuous line charge, the calculation of this parameter is the ratio of total charge weight to total line length. For the discrete charges at uniform separation, this parameter is the ratio of individual charge weight to the separation between charges. For the discrete line charges fired at varying horizontal separations, this parameter is calculated as follows:

$$\frac{\textit{(Total Number of Charges} - 1) * \textit{(Single Charge Weight)}}{\textit{Total Charge Length Projected on Surface}}$$

Shots 7 and 11: Continuous charges, two constant depths:

Length:
7: 56 ft
11: 40 ft

Depth:
7: 8.2 ft
11: 9.4 ft

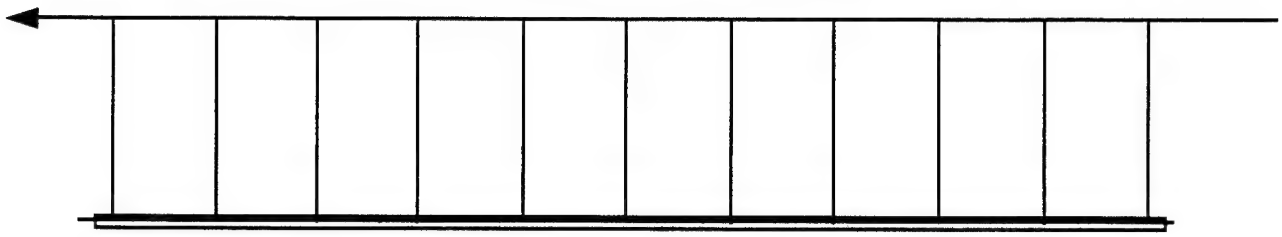

Figure 3. Continuous Line Charge Arrangement at Constant Depth

Shot 8: Continuous charges, "predicted" depths:

Total Length: 56 ft

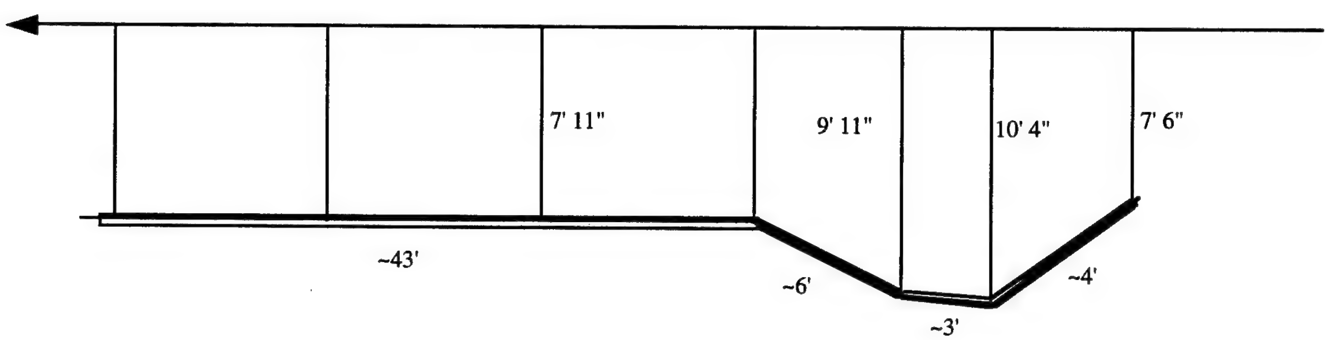

Figure 4. Continuous Line Charge Arrangement at Varying Depths

Shot 6: Eight discrete charges, equally spaced, all at the same depth:

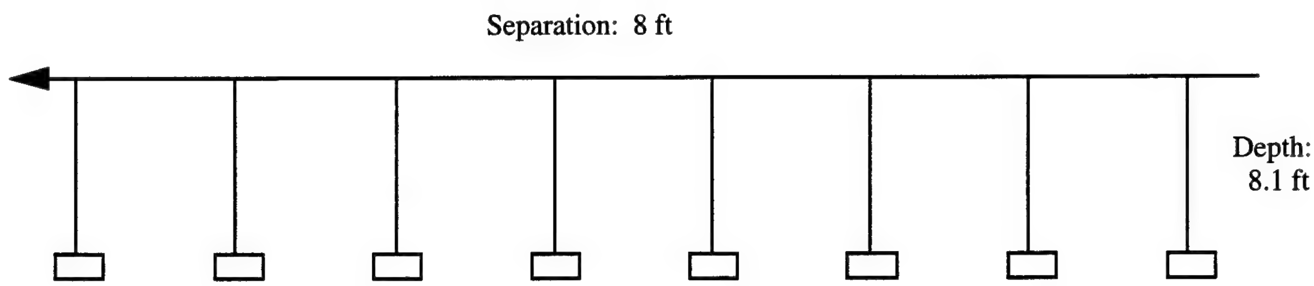

Figure 5. Eight Discrete Charges Arranged at Constant Depth

Shots 2, 9, 10, and 12: Five discrete charges, equally spaced, three depths:

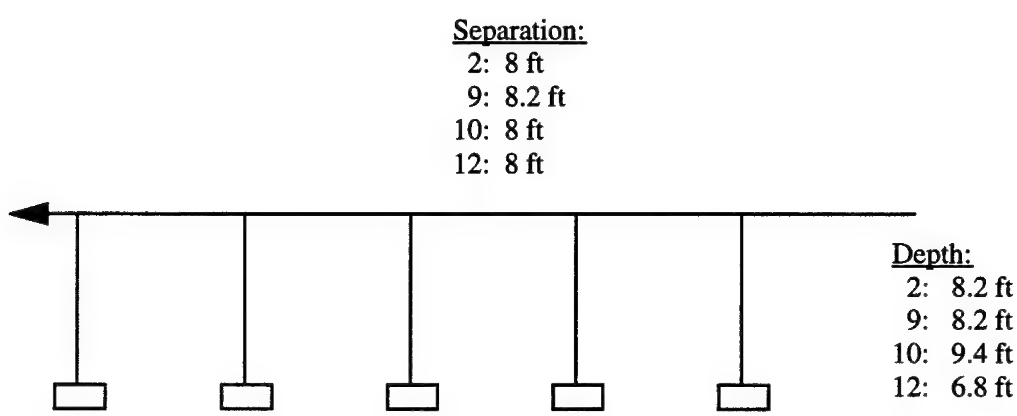

Figure 6. Five Discrete Charges Arranged at Constant Depth

Shot 3: Six discrete charges, five spacings, five depths:

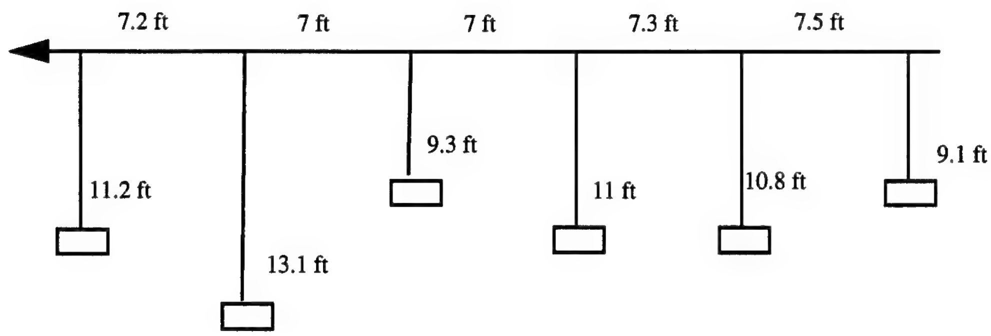

Figure 7. Six Discrete Charges Arranged at Varying Depths

Shot 13: Eight discrete charges, seven spacings, various depths:

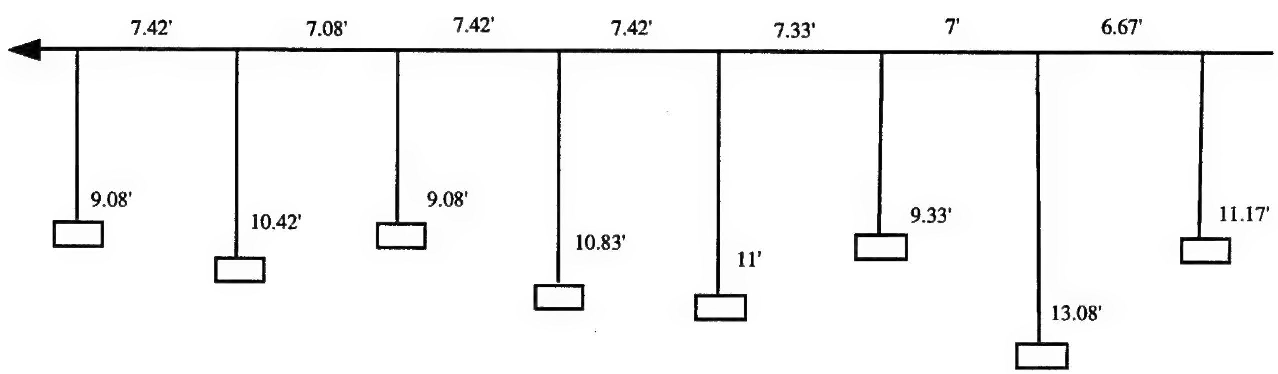

Figure 8. Eight Discrete Charges Arranged at Varying Depths

- Bubble aspect ratio: This quantity is the ratio of line charge length (L) to maximum diameter (D) of the cylindrical bubble produced by a uniform line charge fired at the same depth. The bubble diameter was extrapolated from data obtained on other tests using detonating cord containing a variety of materials. When this ratio approaches unity, the bubble shape approaches that of a sphere and the resultant line charge plume resembles those generated by a concentrated single charge. However, at unity, the bubble is not strictly a sphere since the calculation does not account for the horizontal expansion of the bubble at either end of the line charge.

The following two depth arrangements were chosen for firing these line charge tests:

- Ideal depth: All the line charges were fired at a predetermined depth; these conditions mimic an idealized laboratory-like configuration. Each line charge is assumed to be located at a definite position under a perfectly flat water surface.

- Predicted depths: For the discrete line charge each discrete charge was placed at the depth and separation from its neighbors that was determined by a computer model of the anticipated deployment system.[8] For the continuous line charge the steel rod to which the demolition blocks were taped was twisted to match the configuration predicted by the modeling program. As a dividend, this arrangement also mimics the effect of having the charges located under a water surface that is churned by random sea waves.

Characteristics of the 13 shots fired are listed in the shot log of Table 1. The third column lists the depths at which the line charges were detonated. In this column "pred" ("predicted") indicates that the entire line charge was not at the same depth. In the fourth column the numbers in parentheses are the numbers of individual demolition blocks that were used to make up the respective continuous line charges. Each of the discrete line charges consisted of a number of distinct charges each weighing 10 pounds. Charge separation is the spacing between individual charges in the discrete line charge. Total weight and length refer to the total amount of explosive that was distributed between the ends of each line charge. Linear charge density is the charge weight per unit length as previously described. The last column - titled L/D - is the bubble aspect ratio as previously described.

For these tests, the linear charge density of the charges used on shots 1 and 5 was more than twice that of the charges used on the other shots. In addition, these two shots, as well as shot 4 were fired at depths less than the anticipated cylindrical bubble diameter. (The predicted bubble aspect ratio was less than unity.) As expected, these line charge configurations did not produce plumes high or dense enough for the intended use of the final device. Since the other ten line charges produced plumes of sufficient dimensions to form an effective wall of water, these three shots will not be included in the following discussion. For the remaining ten shots, the linear charge density fell between 1.25 and 1.68 lb/foot and the bubble aspect ratio was greater than 1.3.

Table 1. Shot Log

Shot	Type	Depth (ft)	No. of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	lb / ft	L/D
1	Discrete	12.6	8	3	80	21.0	3.33	0.58
2	Discrete	8.2	5	8	50	32.0	1.25	1.37
3	Discrete	Pred	6	7 to 7.5	60	35.8	1.40	1.53
4	Continuous	8.2	(20)	----	25	20.0	1.25	0.84
5	Discrete	Pred	9	2.25 to 2.75	90	20.1	3.98	0.56
6	Discrete	8.2	8	8	80	56.0	1.25	2.40
7	Continuous	8.2	(56)	----	70	56.0	1.25	2.40
8	Continuous	Pred	(56)	----	70	53.7	1.30	2.30
9	Discrete	8.2	5	8	50	32.0	1.25	1.37
10	Discrete	9.4	5	8	50	32.0	1.25	1.37
11	Continuous	9.4	(40)	----	50	40.0	1.25	1.70
12	Discrete	6.8	5	8	50	32.0	1.25	1.37
13	Discrete	Pred	8	6.75 to 7.4	80	50.3	1.39	2.10

CHARGE DEPLOYMENT

The field layout for the tests is shown on Figure 9. The numbers adjacent to several of the points on the sketch are arbitrary identification numbers assigned by the survey team. The rigging was designed to ensure that the center of each line charge was placed at the same location relative to the cameras for each shot. This is point 15, also labeled SZ (Surface Zero). Fixed lengths of polypropylene line were attached to points 12 and 14 on the edge of the quarry; these lines joined at point 16 from which a breakaway line was attached to one end of the line charge surface line. The other end of the line charge surface line was attached to point 7 in front of camera 2. Replacing the breakaway surface line for each shot and pulling the rig taut placed each line charge arrangement in the same location so that the cameras, conductivity gauges and microwave towers (points 6 and 8 on the survey) could remain fixed.

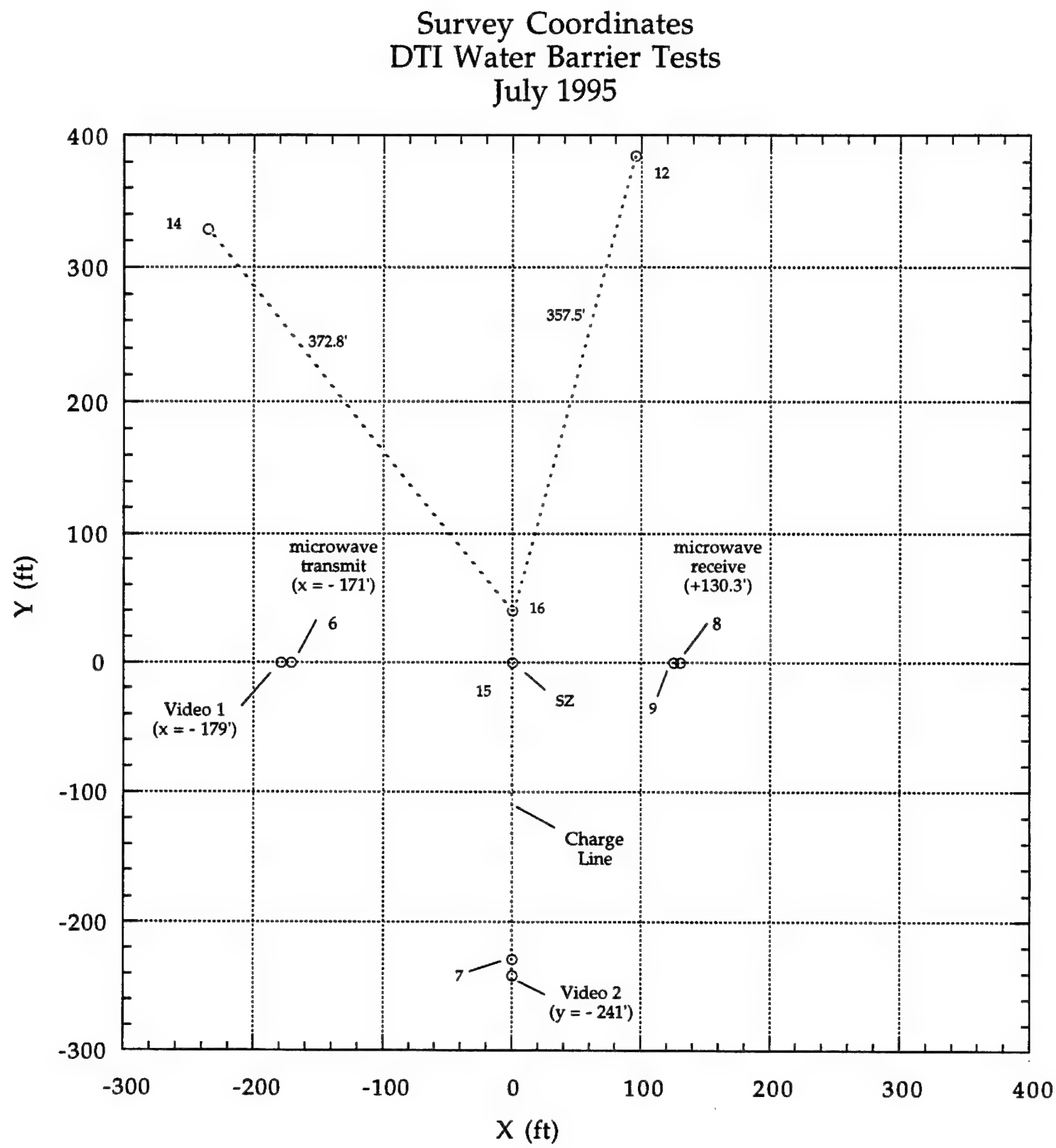

Figure 9. Plan View of Test Setup

VIDEO CAMERA DATA

SETUP

Two camcorders running at 30 frames per second were used for each shot. This frame rate is determined electronically and cannot be changed. Super-VHS format was used because of the superior resolution possible in that format. The cameras were operated manually: each was started a few seconds before and stopped a few seconds after each shot. As a result, records for all shots are available on a few feet of video tape. It was not practical - or necessary - to synchronize the shutters on the two cameras since they were several hundred feet apart.

Locations of the two cameras are indicated on Figure 9. Camera 1 was located on a hill at the side of the quarry hole where it recorded images of the lengths and heights of the line charge plumes produced by the explosions. Camera 2 was placed at the end of the surface charge line and aimed along the axis of the line charges to record the diameters of the line charge plumes as a function of time. The position of each camera was located with respect to the center of the line charge length so that the optic axes of the two cameras were perpendicular to one another. A fiducial of known dimensions was included in the field of view of each camera to obviate the need to calibrate the focal lengths of the camera lenses.

IMAGE DIGITIZATION

Height, length, and diameter of the line charge plumes were determined from the video tape images digitized with a Data Translation, Inc., video capture board (DT 3851-8) installed in a DOS/Windows-compatible computer. A maximum of 16 frames at a time were captured from the video tape. The images were held in memory long enough to use known dimensions visible in each frame to determine a scale from which the dimensions of the line charge plumes could be calculated --all by the software supplied with the image capture board. Data was logged and transferred to a plotting program to produce the graphs included in this report.

The smallest observable increment was the width of a pixel on the monitor screen. For all of the video tapes this was about 0.2 feet (2.5 inches). As a measure of precision this is somewhat deceiving because the tenuous edges of the plumes make precise, repeatable positioning of the cursor difficult. The airborne water mist on the outer edges of the plumes is difficult to distinguish from the background on the shaded side of the plumes. It is reasonable to presume that the measurements reported in the following are accurate to within less than two feet.

Zero time on each tape record was chosen to be the first frame in which whitening of the water surface was observed. Measurement was terminated on each record either when the plume became so tenuous that it could not be distinguished from the background, or when the plume passed out of the field of view of the camera at the top or sides of the frame.

DEFINITIONS

The following terms are used to describe the dimensions of the line charge plumes observed on the video tape records:

- *Height*: Refers to the dimension measured vertically from the water surface to a particular feature of the plume on the video tape exposed in camera 1. In cases where several jets initially rise above the rest of the water, each jet was measured separately and the average of all has been reported in the graphs.

- *Length*: Refers to the dimension measured parallel to the line charge as seen from camera position 1 on the hill.

- *Diameter*: Refers to the dimension measured perpendicular to the line charge as seen from camera position 2.

RESULTS

DATA REDUCTION

Plume dimensions were measured on video tape images of ten shots of the 1995 DTI series for this discussion. As indicated above, three of the thirteen shots did not produce adequate plumes and are not included here.

- Shots 2, 6, 9, 10, and 12 consisted of discrete charges at an 8-foot separation but differing detonation depths. Shots 2, 6, and 9 were fired at 8.2 feet, shot 10 was fired at 9.4 feet, and shot 12 was fired at 6.8 ft.

- Shots 7 and 11 were continuous line charges. The length of the charge on shot 7 (the shallower of the two) was roughly 1.5 times that on shot 11.

- Shot 8 (continuous) and shot 13 (discrete) were intended to compare the two types of line charge configurations at "predicted" depths.

- Shot 3 was a line charge that employed discrete charges placed at depths and separations predicted by the computer model. Poor contrast in the video images precluded late time measurements; data serves only to ratify shot 13.

For this discussion the ten shots that were reduced have been grouped to simplify the analysis of the data. There is some necessary overlapping of the shots in the groupings.

- An overall perspective of the test series is provided by the first group of shots. Four shots (6, 7, 8, and 13) were considered together since they incorporate the effects of explosive distribution and depth variations. The four shots show only minor differences among the measured plume dimensions.

- The effects of varying firing depth are examined both for continuous line charges (shots 7 and 11) and for discrete line charges (shots 9, 10, and 12).

- The effects of varying discrete charge length are illustrated by shots 2, 6, and 9. Since shots 2 and 9 were fired under the same conditions, they provide information about the repeatability of the line charge plume phenomena.

- Repeatability is also examined for discrete charges at "predicted" depths by comparing shots 3 and 13.

- Finally, the effect of sequential vs. simultaneous detonation of discrete charges on the general shape of the plume is examined. This was done with a qualitative comparison of shots 2 and 9 from this series with shot 3 from a series of tests conducted in the Hi Test Laboratories quarry in the summer of 1993. Since the charge weights and explosive were the same on both series of tests, a direct comparison of dimensions is meaningful. However, note that there is no accepted method for scaling the plumes produced by different charges or charge configurations to a common basis.

CHARGE DISTRIBUTION EFFECT

Vertical and horizontal plume dimensions were measured on four shots: 6, 7, 8, and 13 (see Table 2). These shots represent the differing effects of the continuous and the discrete line charge configurations as well as the differences between firing at "ideal" and at "predicted" depths. Shots 6 and 13 are discrete line charges and shots 7 and 8 are continuous line charges. All are long enough (≥ 50 feet) to allow a wall of water over the central portion of the line charge length that is expected to be independent of any end effects.

It is possible to investigate the effects of changing various parameters by pairing the shots as follows:

- 6 vs. 7: continuous vs. discrete at the "ideal" constant depth
- 8 vs. 13: continuous vs. discrete at "predicted" depths
- 7 vs. 8: continuous line charge at ideal vs. predicted depths; constant weight
- 6 vs. 13: discrete line charge at ideal vs. predicted depths; constant weight

Figures 10 through 14 present, as a function of time, the height, diameter, and length at 11.5 and 25 feet above the water surface of the line charge plumes produced by these four shots. The dimensions of the plumes produced by these shots are remarkably similar. The shot 6 data seem to indicate that the number of discrete charges at the depth and spacing used for this shot produce a plume that is definitely higher and slightly greater in diameter and length than the other three in this group. As previously noted, data measurement was terminated on each record when the plume could not be distinguished from the background or when the plume passed out of the camera's field of view.

Figure 10 shows that, early in plume formation, shot 6 produced a 30% higher plume than the other three shots, which implies that a properly deployed discrete line charge can become effective faster against sea skimmers than a continuous line charge can. (Note that shot 13 involved a discrete line charge fired at a "predicted" depth.) This may imply that the means of deploying discrete line charges for barrier generation has a minor effect on the overall height of the wall of water that is thrown into the air. Because there is no observable effect on the height of the plumes generated by shots 7 and 8, the means of deploying the continuous line charges may not be critical. However, since there is only one shot at each condition, the greater height attained by the plume from shot 6 may not be characteristic.

Table 2. Charge Distribution Effect (Figures 10 through 14)--
Dimension Data for Shots 6, 7, 8, and 13

Shot	Type	Depth (ft)	No. of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	lb / ft	L/D
6	Discrete	8.2	8	8	80	56.0	1.25	2.40
7	Continuous	8.2	(56)	----	70	56.0	1.25	2.40
8	Continuous	Pred	(56)	----	70	53.7	1.30	2.30
13	Discrete	Pred	8	6.75 to 7.4	80	50.3	1.39	2.10

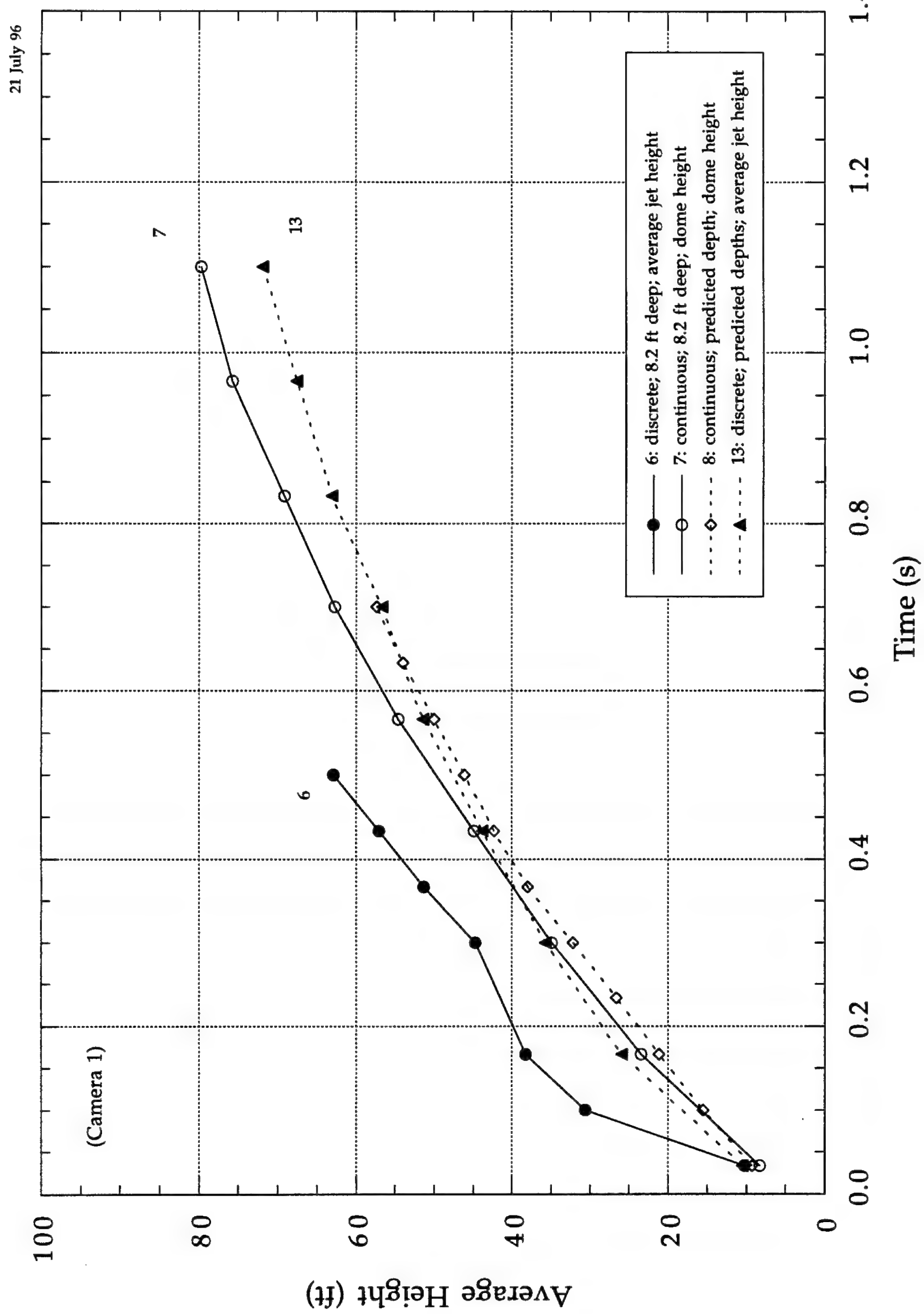

Figure 10. Barrier Height: Shots 6, 7, 8, and 13

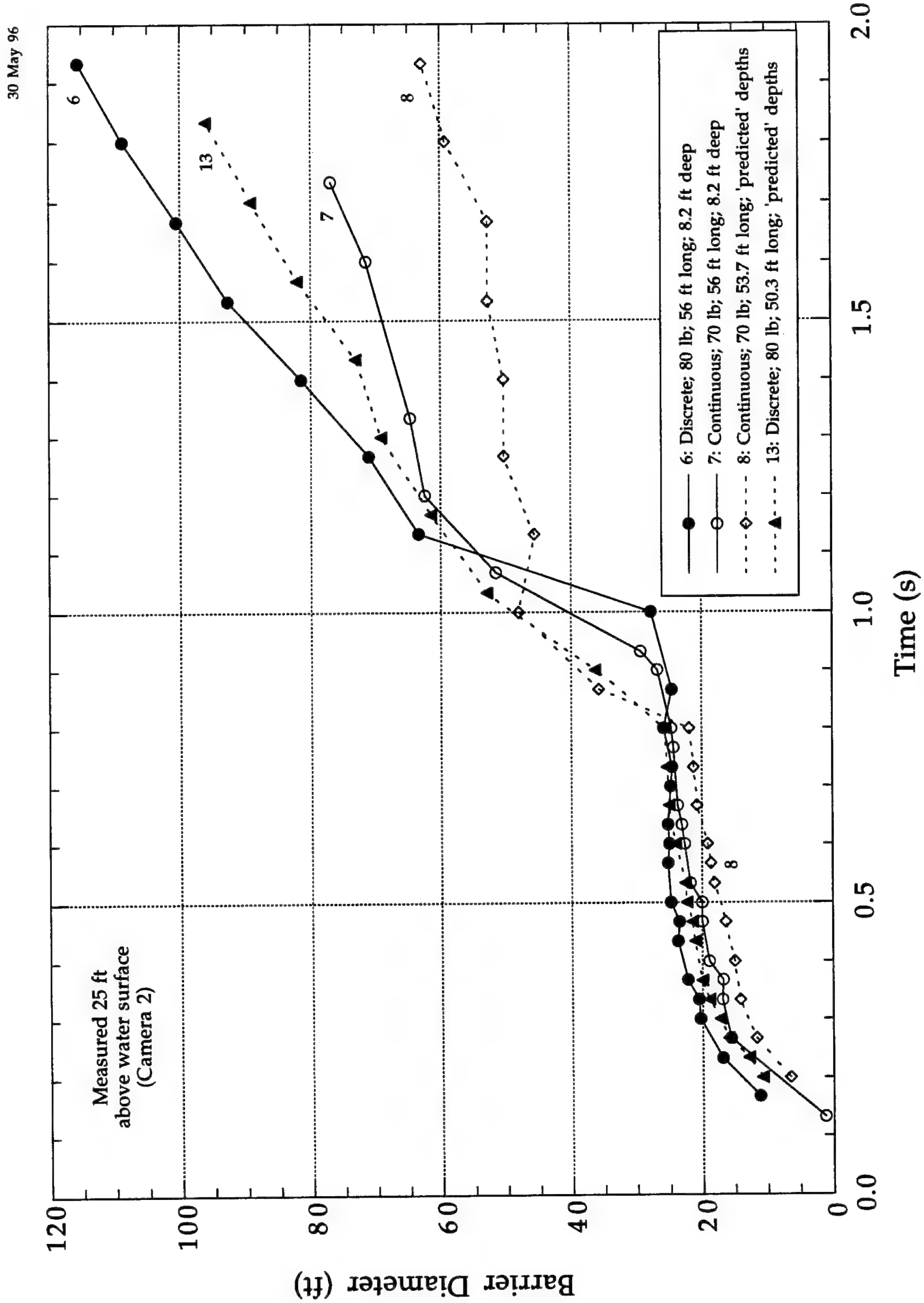

Figure 11. Barrier Diameter at 25-Foot Altitude: Shots 6, 7, 8, and 13

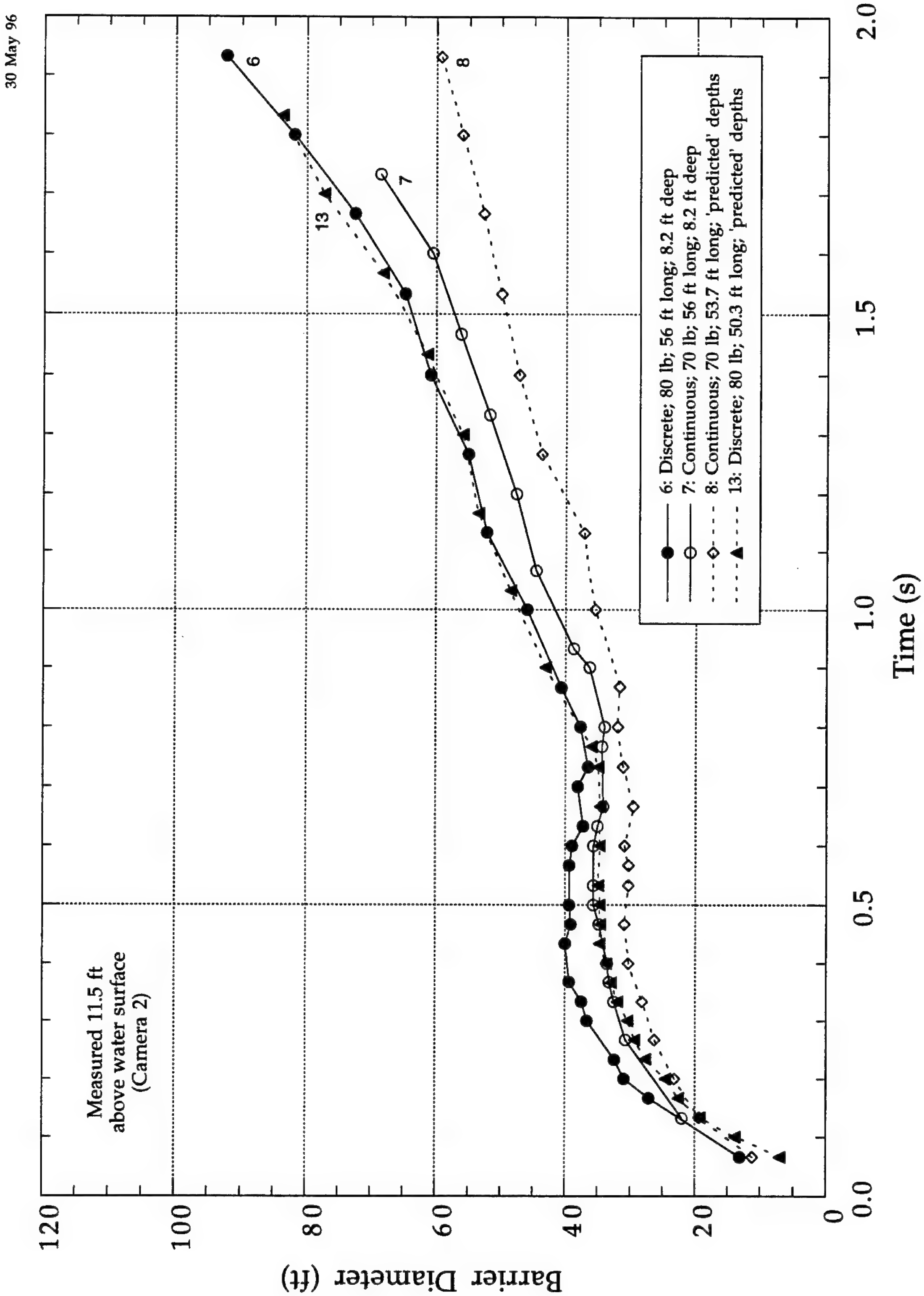

Figure 12. Barrier Diameter at 11.5-Foot Altitude: Shots 6, 7, 8, and 13

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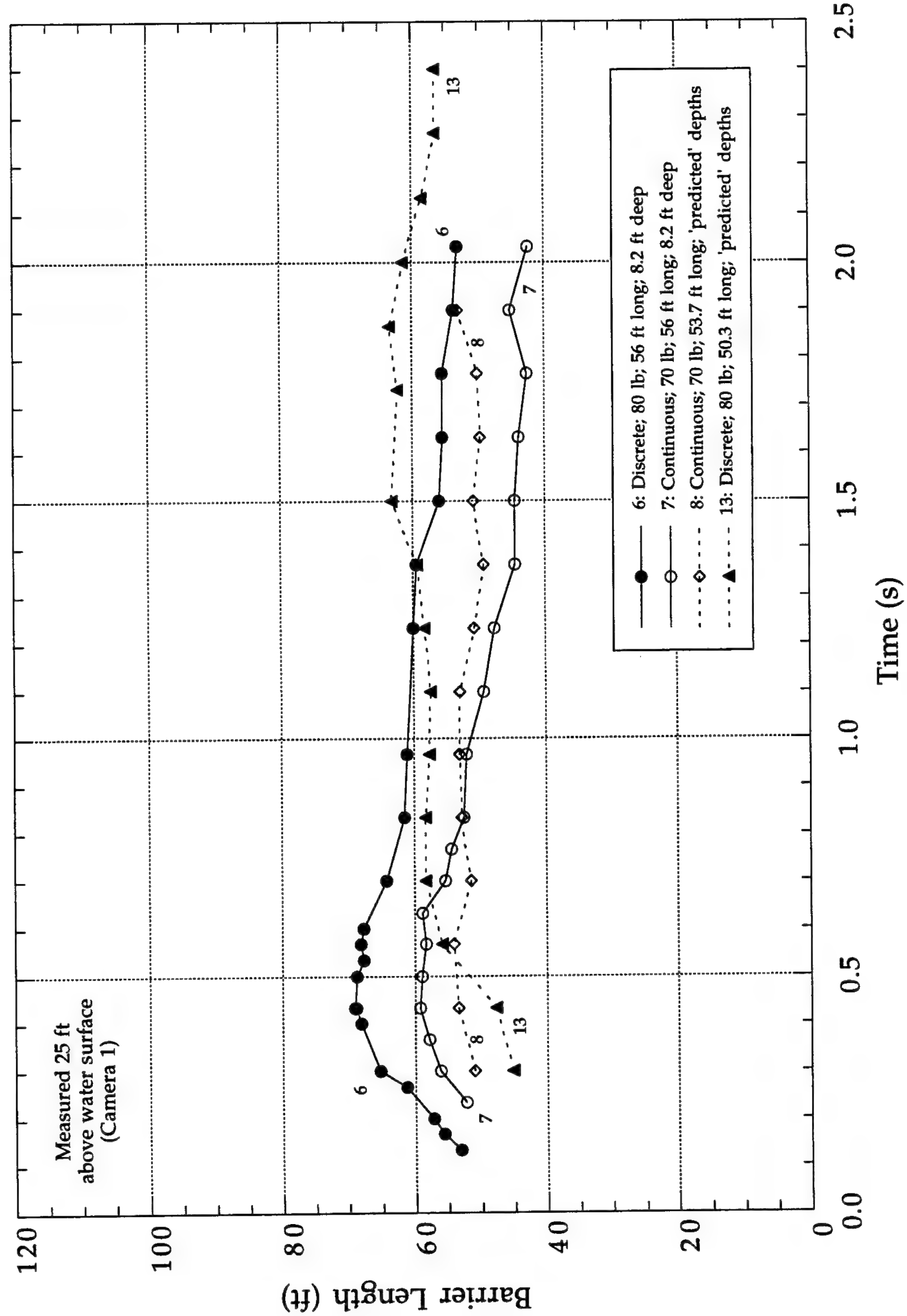

Figure 13. Barrier Length at 25-Foot Altitude: Shots 6, 7, 8, and 13

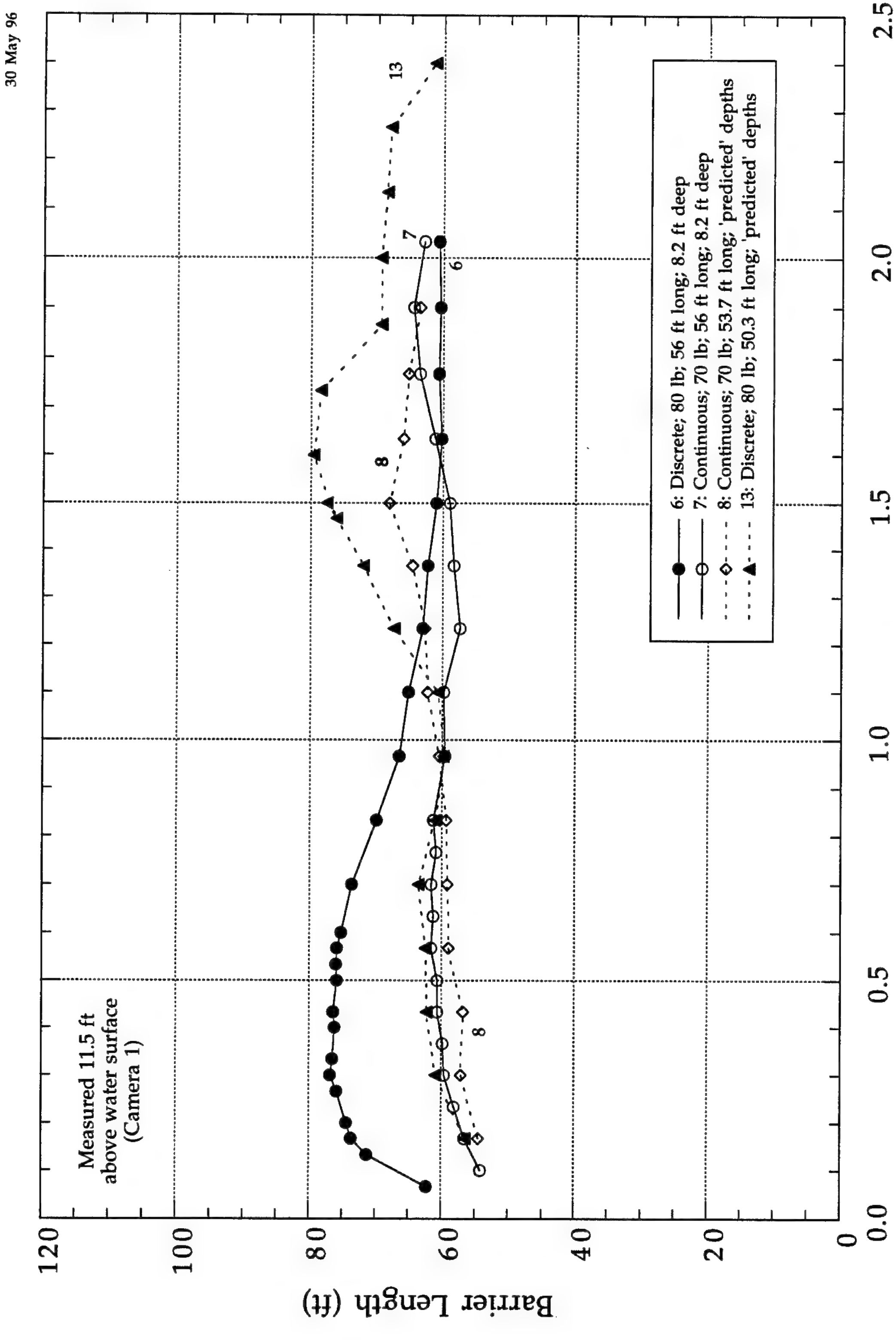

Figure 14. Barrier Length at 11.5-Foot Altitude: Shots 6, 7, 8, and 13

Referring to Figure 11, the diameter at 25 feet above the water surface (the lateral dimension seen on camera 2) begins to grow more rapidly between 0.8 and 1.0 seconds after the first surface whitening is observed. The diameter and sometimes the length of a plume frequently show a sudden increase when the bottom surface of the bubble cavity pushes through the developing central plume generating secondary plumes in the front and rear of the line charge. For both the continuous and the discrete line charges fired at the predicted depths (shots 8 and 13), the sudden change in diameter occurs earlier (at 0.8 seconds) than does the change in the plume produced by the two types of line charge fired at a constant depth of 8.2 feet. In addition, the discrete line charges (shots 6 and 13) produce plumes marginally wider and longer than observed above the continuous line charges on shots 7 and 8. Other than the timing of the diameter growth rate change, these four shots show only minor variations in diameter at the 25-foot altitude from one shot to the next.

On Figure 12 the diameters of the plumes formed by the four shots at 11.5 feet above the water surface are remarkably similar. The discrete line charges have a slight (~ 10%) edge on the best of the continuous line charge shots. There is no sudden change in growth rate similar to that observed at the 25-foot altitude.

In Figures 13 and 14, plume lengths at the two heights of 25 and 11.5 feet can be distinguished on the basis of charge type. The discrete line charges produced 10-20 % longer plumes than did the continuous line charges. All the line charges on these four shots were within a few feet of the same length, so this difference is not significant.

Shot 6 (constant depth) and shot 13 ("predicted" depth) both were discrete line charges; they produce plume dimensions that are marginally greater than those produced by the continuous line charges of shots 7 and 8. In practice, line charge depths may vary either as predicted by the computer model of a typical deployment scheme, or as a result of wind-driven surface waves. A variation in line charge depth within reasonable bounds appears to have no serious effect on the production of a usable water barrier.

It does not appear useful to further dissect the data from these four shots. Except for shot 6, whose dimensions are generally larger than the others, the four shots exhibit minor distinctions but no major differences that are expected to affect the production of a water barrier.

FIRING DEPTH EFFECT

Line charge firing depth relative to bubble diameter is the primary determinant of the amount and the maximum altitude reached by the water ejected into the air above an underwater detonation. In this section the effect of firing depth on the dimensions of the plumes produced by continuous and by discrete line charge configurations is examined.

Continuous

Shots 7 and 11 were two continuous line charges of the same linear charge density fired at different depths (see Table 3). The line charge on shot 7 was 56 feet long and was fired at a depth of 8.2 ft. The shot 11 line charge was 40 feet long and was fired at a depth of 9.4 feet. Both depths were greater than the anticipated radius of the gas bubble produced at that depth. Both line charges were strings of M113 demolition blocks laid end-to-end along a length of detonating cord, as previously described in Figure 3.

Vertical and horizontal dimensions of the plumes produced by these line charges are shown in Figures 15 to 19. The shallower line charge produces a plume with a maximum height almost twice that of the deeper line charge. An important point to understand in the comparison of plume heights is that the barrier plume height dimension does not necessarily indicate the quantity of water that is present within the plume. The microwave absorption and conductivity probe measurements that were recorded in the field test will be analyzed in another report to get a better understanding of the quantity of water within the barrier plume cross section.

The diameters and lengths of the plumes, measured at 11.5 and at 25 feet above the original water surface, do not differ greatly between the shots - despite the fact that the length of one charge is almost 50% greater than the other. The shorter line charge (shot 11) was detonated at a greater depth (9.4 feet) than was the longer line charge; the apparently anomalous equality of plume length and diameter for this charge may be due to the time at which the bottom of the bubble rises through the inside of the plume; the details of this event are strongly dependent on the depth at which the line charge is detonated.

Discrete

Shots 9, 10, and 12 were discrete line charges fired at three different detonation depths (see Table 4). Plume dimensions are plotted in Figures 20 through 24. All shots had a total explosive weight of 50 pounds and were 32 feet long. Shot 12 was fired at 6.8 feet, shot 9 at 8.2 feet, and shot 10 at 9.4 feet. The two shallower charges produced plumes with greater maximum heights; the 6.8-foot (shot 12) had a slight advantage, although the difference between the 6.8- and the 8.2-foot depths does not appear to be significant.

Diameters and lengths of the plumes on these three shots appear to track one another, though the shallowest charge--shot 12--produces a generally narrower, higher, and more ephemeral plume than the other two. Shot 12, fired at 6.8 feet, produces a plume that appears to contain less water than the other two because there is less water above the line charge to contribute to the plume.

CHARGE LENGTH EFFECT

The discrete line charges used on shots 2, 6 and 9 all were fired at a depth of 8.2 feet with a charge separation of 8 feet (see Table 5). Shot 2 and 9 line charges included five discrete 10-lb units and were 32 feet long. The line charge on shot 6 was 56 feet long and was built from eight discrete 10-lb units. Plume dimensions for these three shots are shown in Figures 25 to 29.

Table 3. Firing Depth Effect (Figures 15 through 19)--
Dimension Data for Shots 7 and 11

Shot	Type	Depth (ft)	No. of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	lb / ft	L/D
7	Continuous	8.2	(56)	----	70	56.0	1.25	2.40
11	Continuous	9.4	(40)	----	50	40.0	1.25	1.70

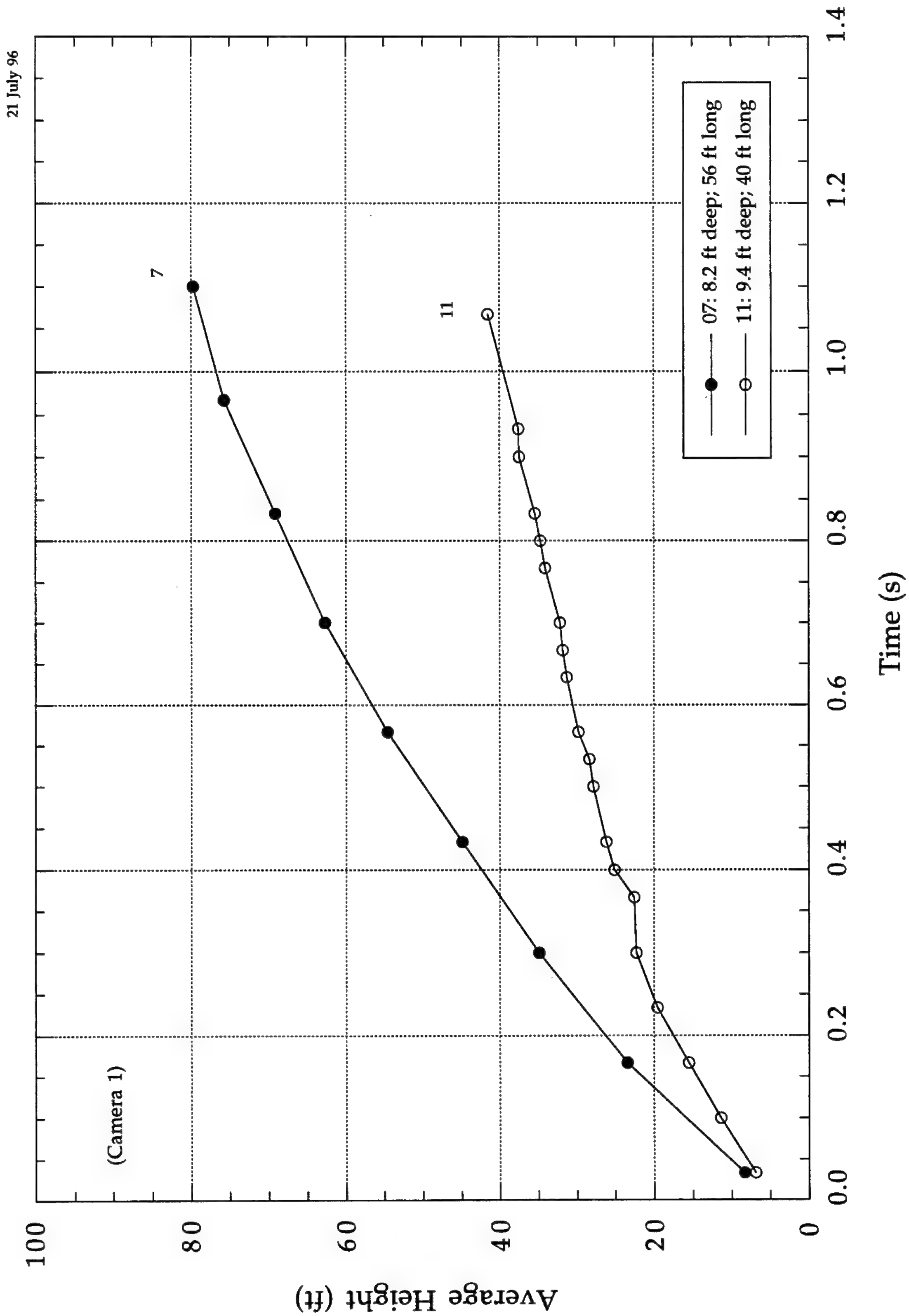

Figure 15. Barrier Height: Shots 7 and 11

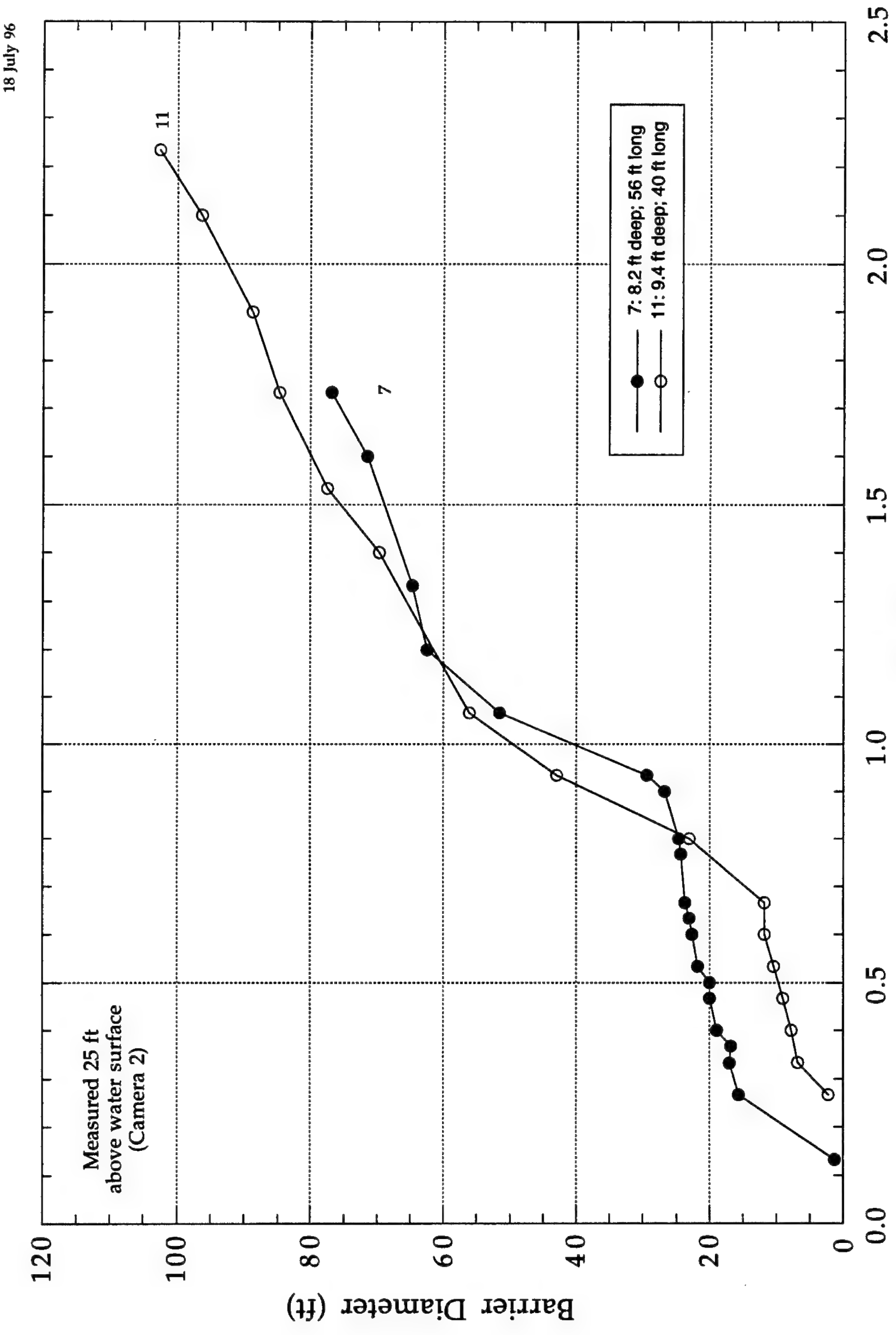

Figure 16. Barrier Diameter at 25-Foot Altitude: Shots 7 and 11

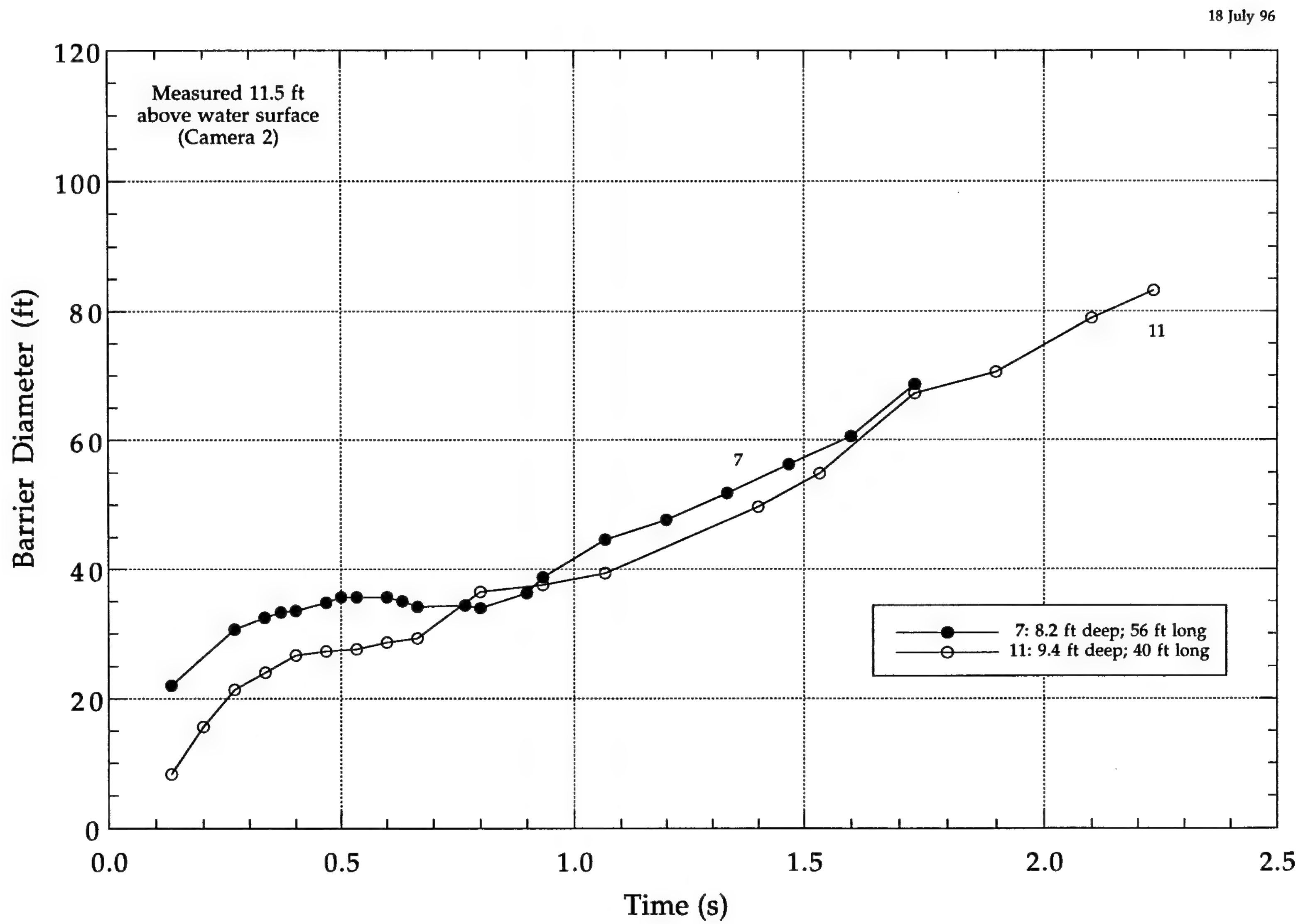

Figure 17. Barrier Diameter at 11.5-Foot Altitude: Shots 7 and 11

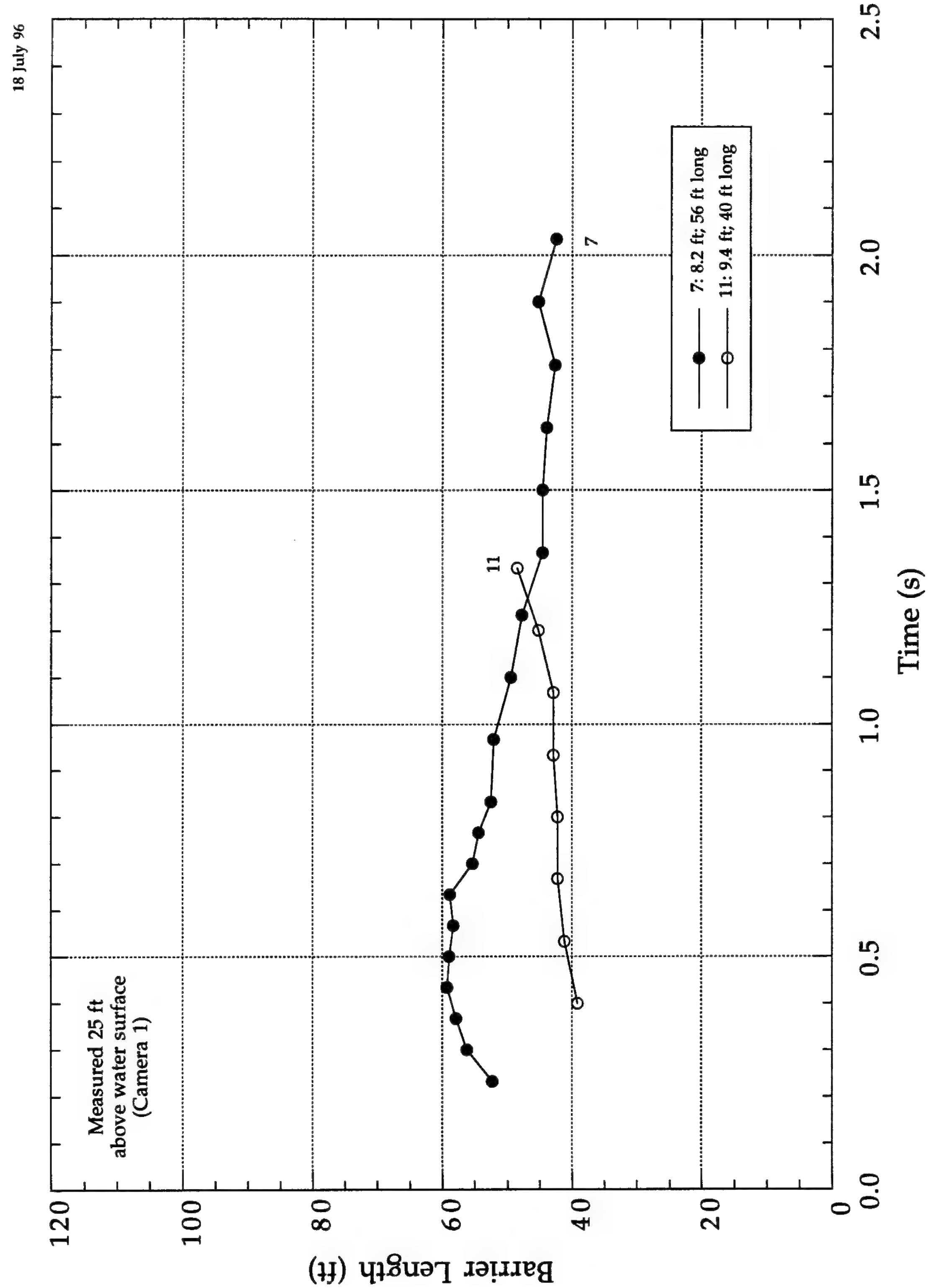

Figure 18. Barrier Length at 25-Foot Altitude: Shots 7 and 11

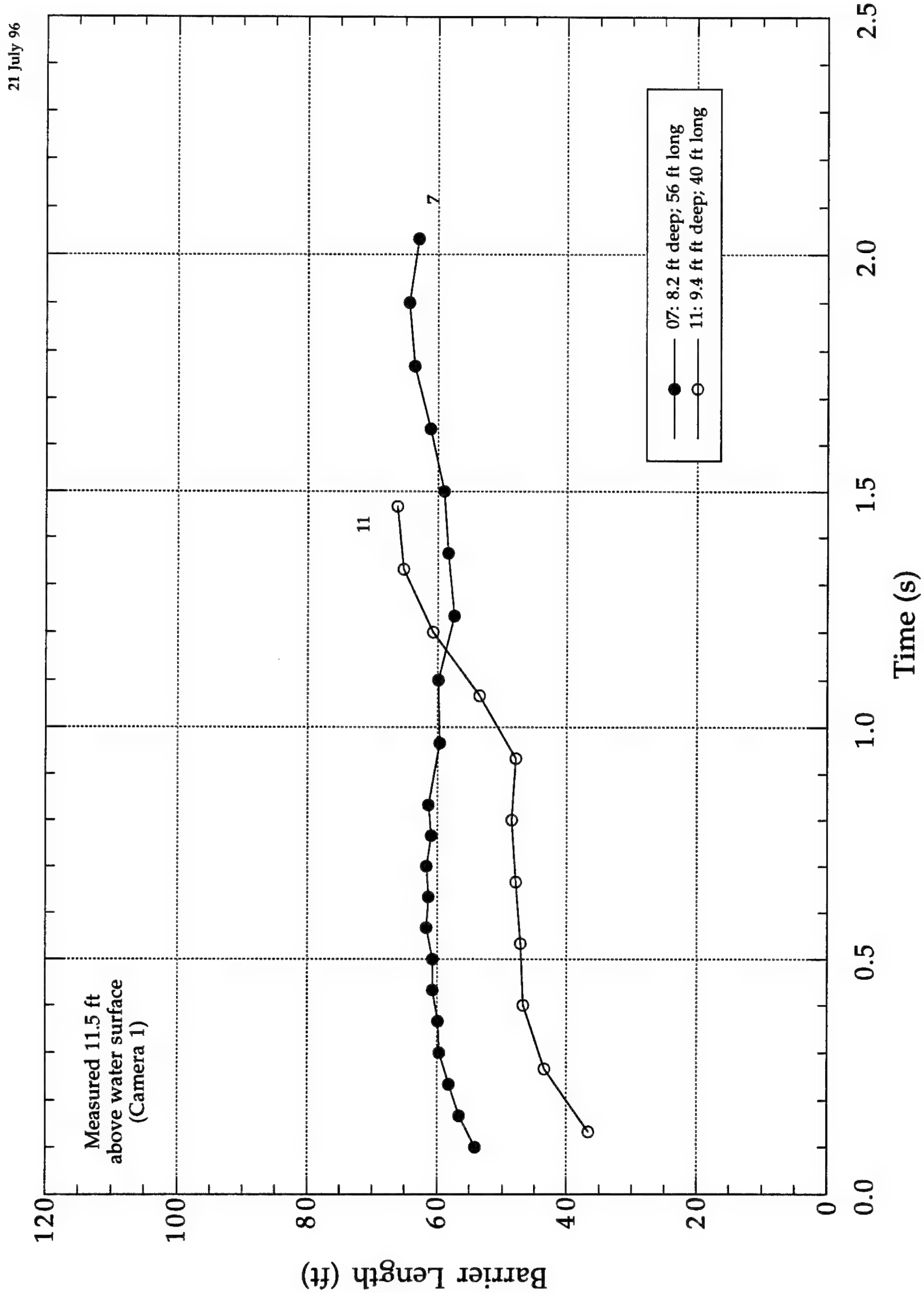

Figure 19. Barrier Length at 11.5-Foot Altitude: Shots 7 and 11

Table 4. Firing Depth Effect (Figures 20 through 24)--
Dimension Data for Shots 9, 10, and 12

Shot	Type	Depth (ft)	No. of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	lb / ft	L/D
9	Discrete	8.2	5	8	50	32.0	1.25	1.37
10	Discrete	9.4	5	8	50	32.0	1.25	1.37
12	Discrete	6.8	5	8	50	32.0	1.25	1.37

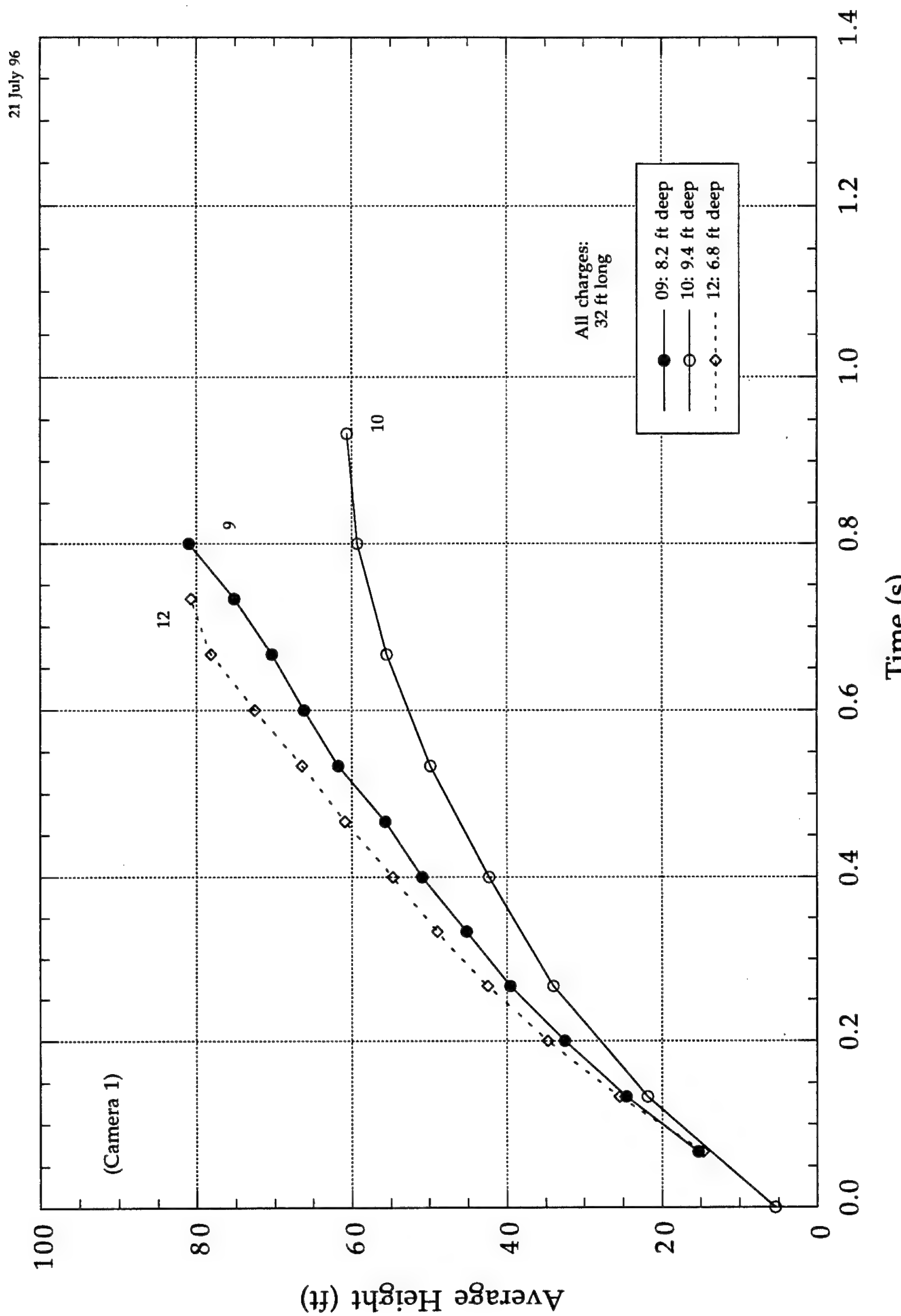

Figure 20. Barrier Height: Shots 9, 10, and 12

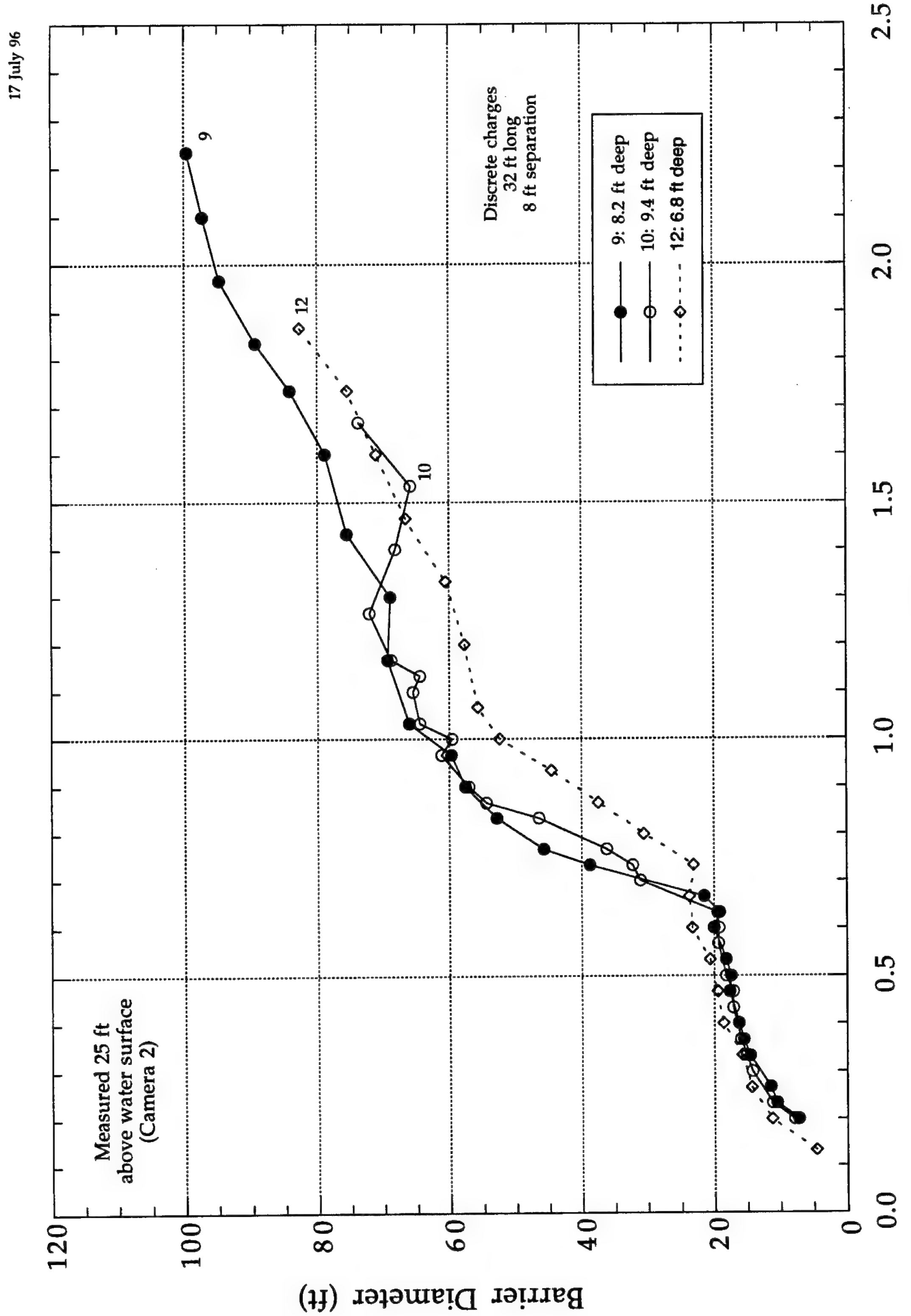

Figure 21. Barrier Diameter at 25-Foot Altitude: Shots 9, 10, and 12

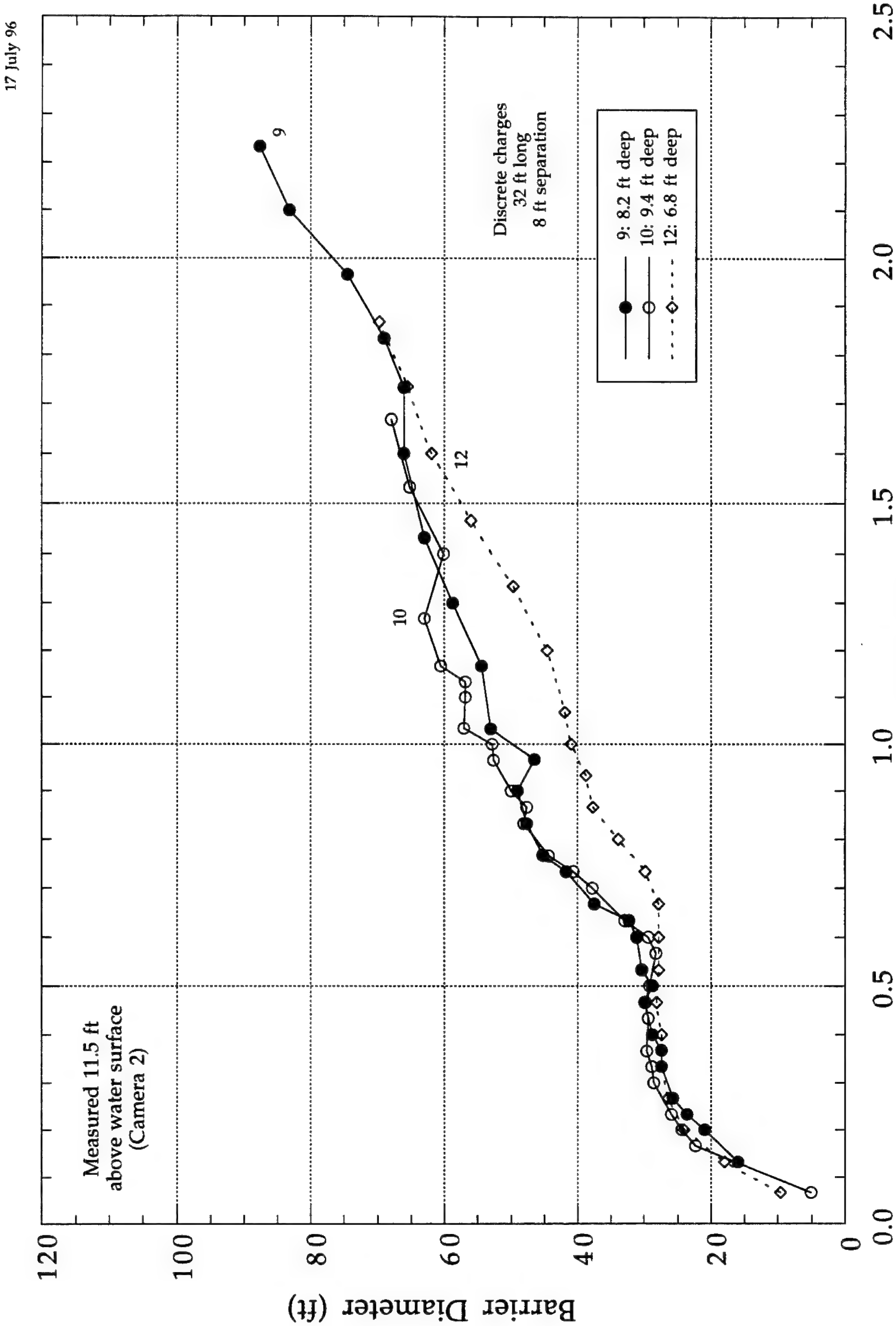

Figure 22. Barrier Diameter at 11.5-Foot Altitude: Shots 9, 10, and 12

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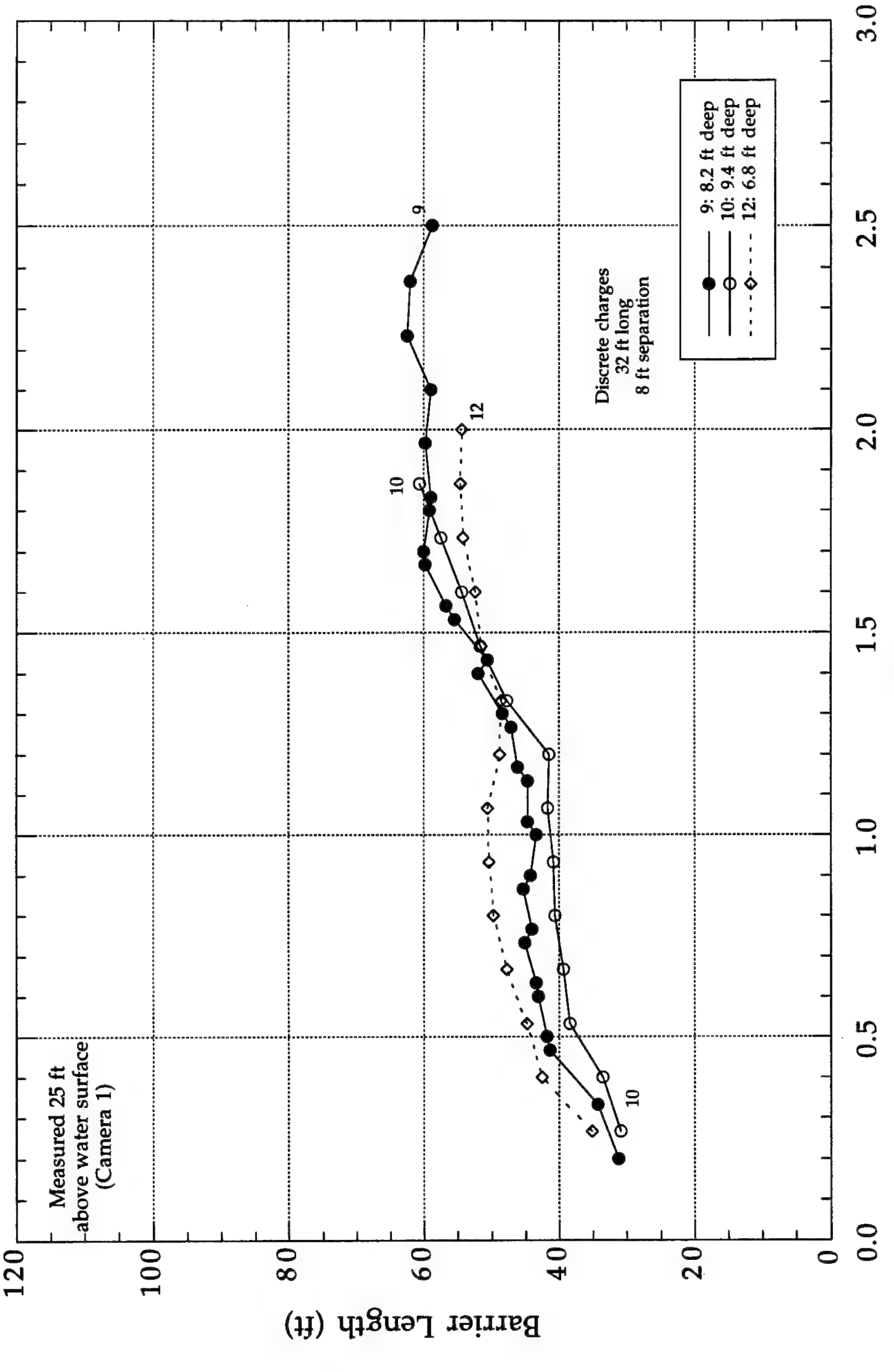

Figure 23. Barrier Length at 25-Foot Altitude: Shots 9, 10, and 12

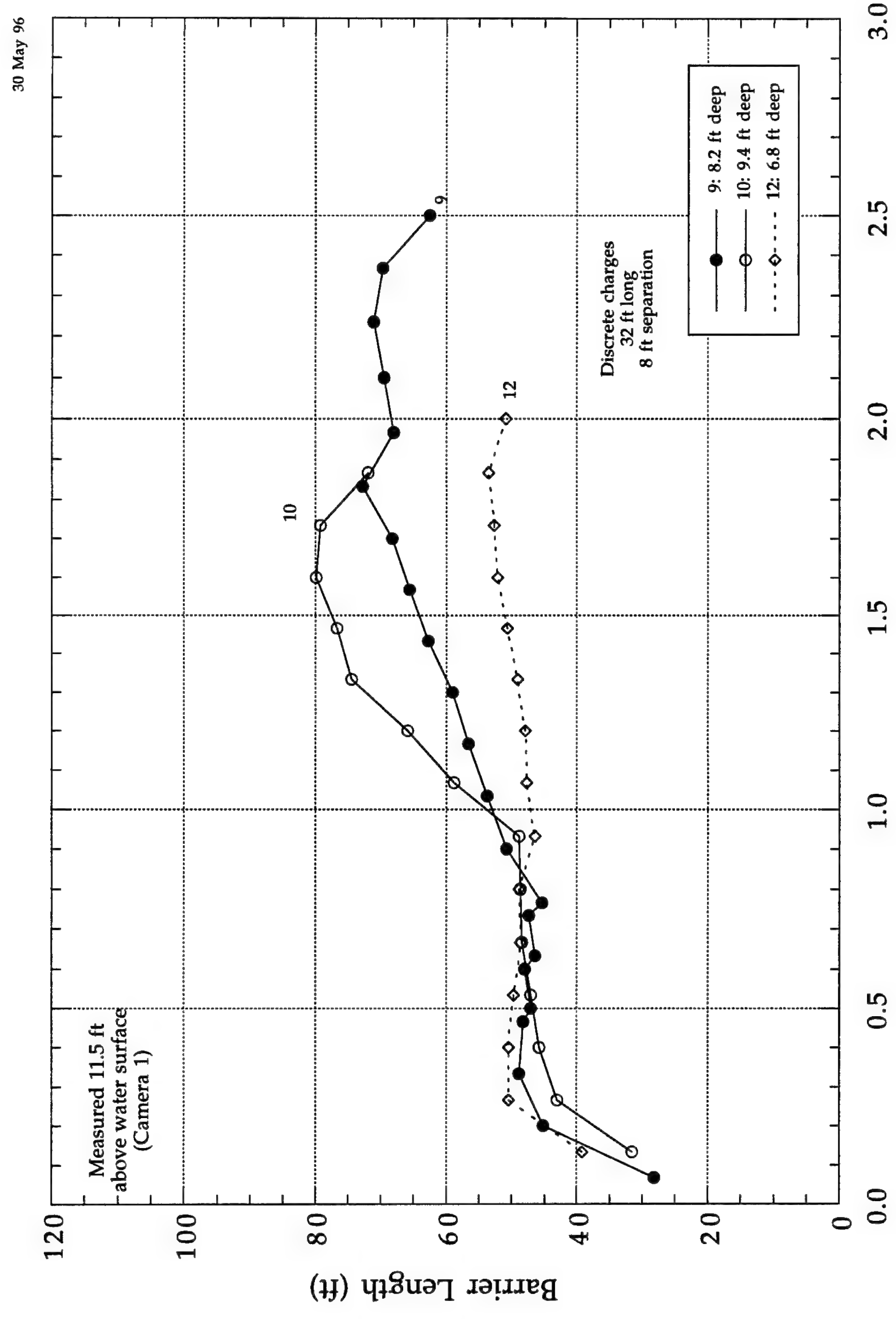

Figure 24. Barrier Length at 11.5-Foot Altitude: Shots 9, 10, and 12

Table 5. Charge Length Effect (Figures 25 through 29)--
Dimension Data for Shots 2, 6, and 9

Shot	Type	Depth (ft)	No. of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	lb / ft	L/D
2	Discrete	8.2	5	8	50	32.0	1.25	1.37
6	Discrete	8.2	8	8	80	56.0	1.25	2.40
9	Discrete	8.2	5	8	50	32.0	1.25	1.37

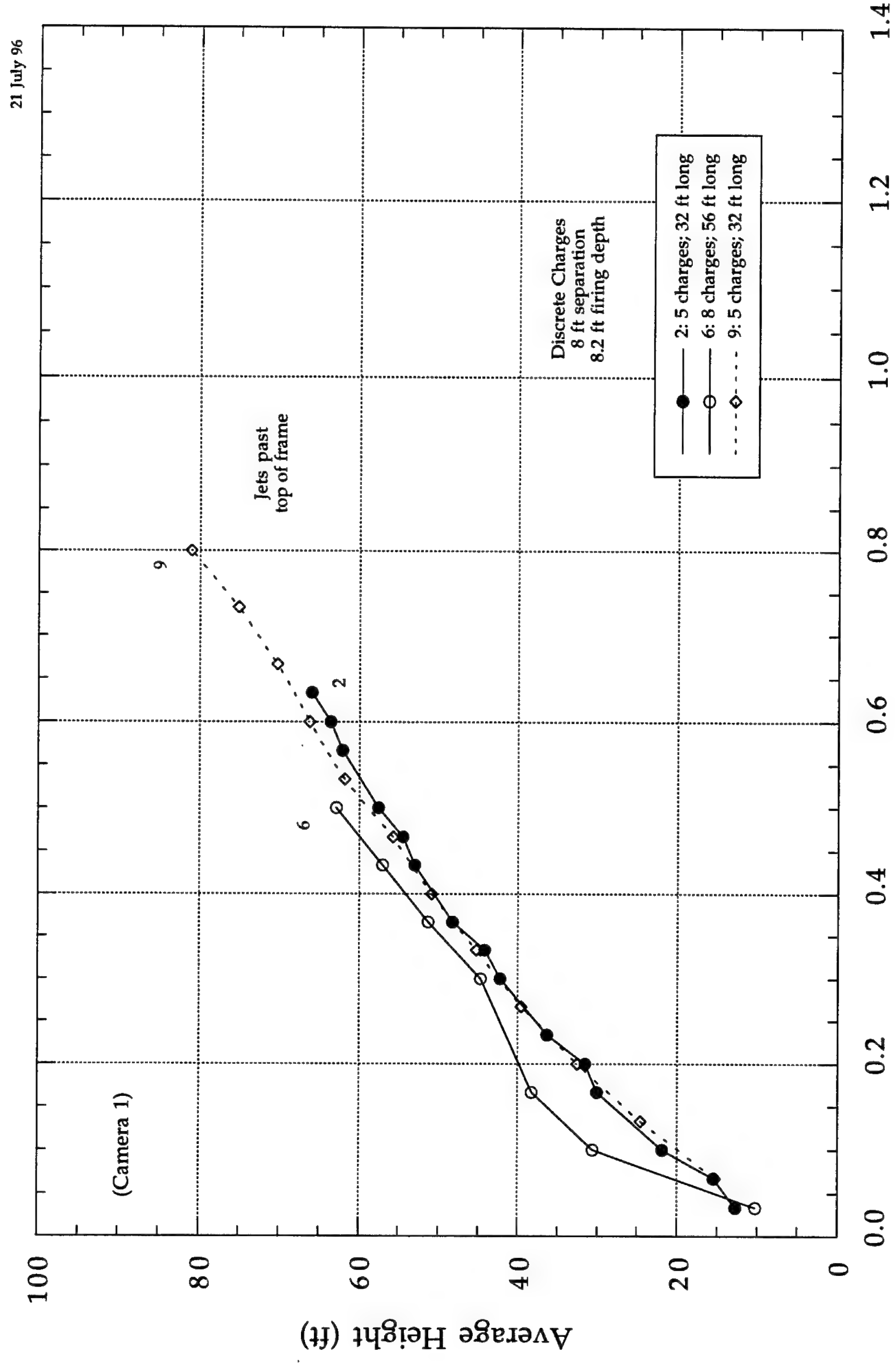

Figure 25. Barrier Height: Shots 2, 6, and 9

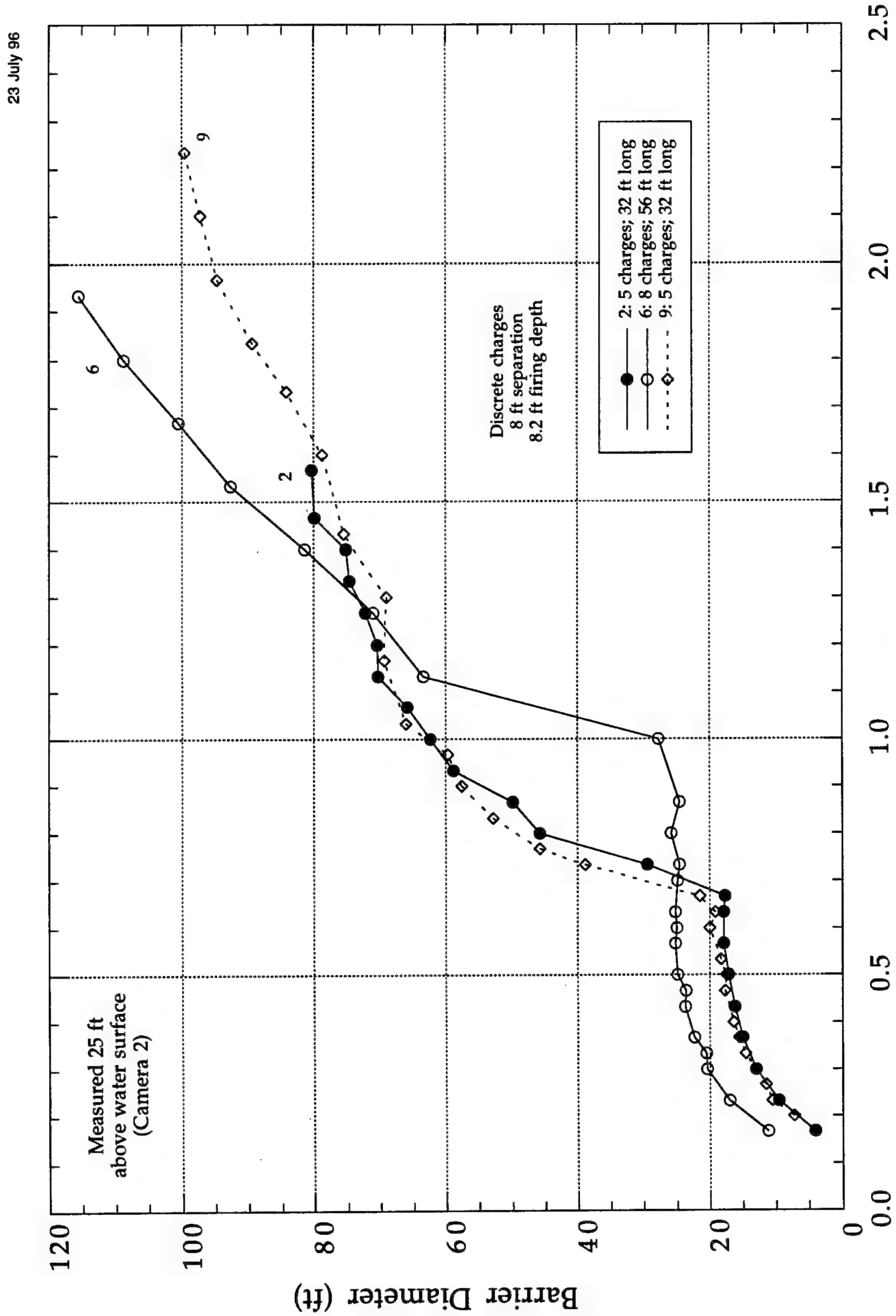

Figure 26. Barrier Diameter at 25-Foot Altitude: Shots 2, 6, and 9

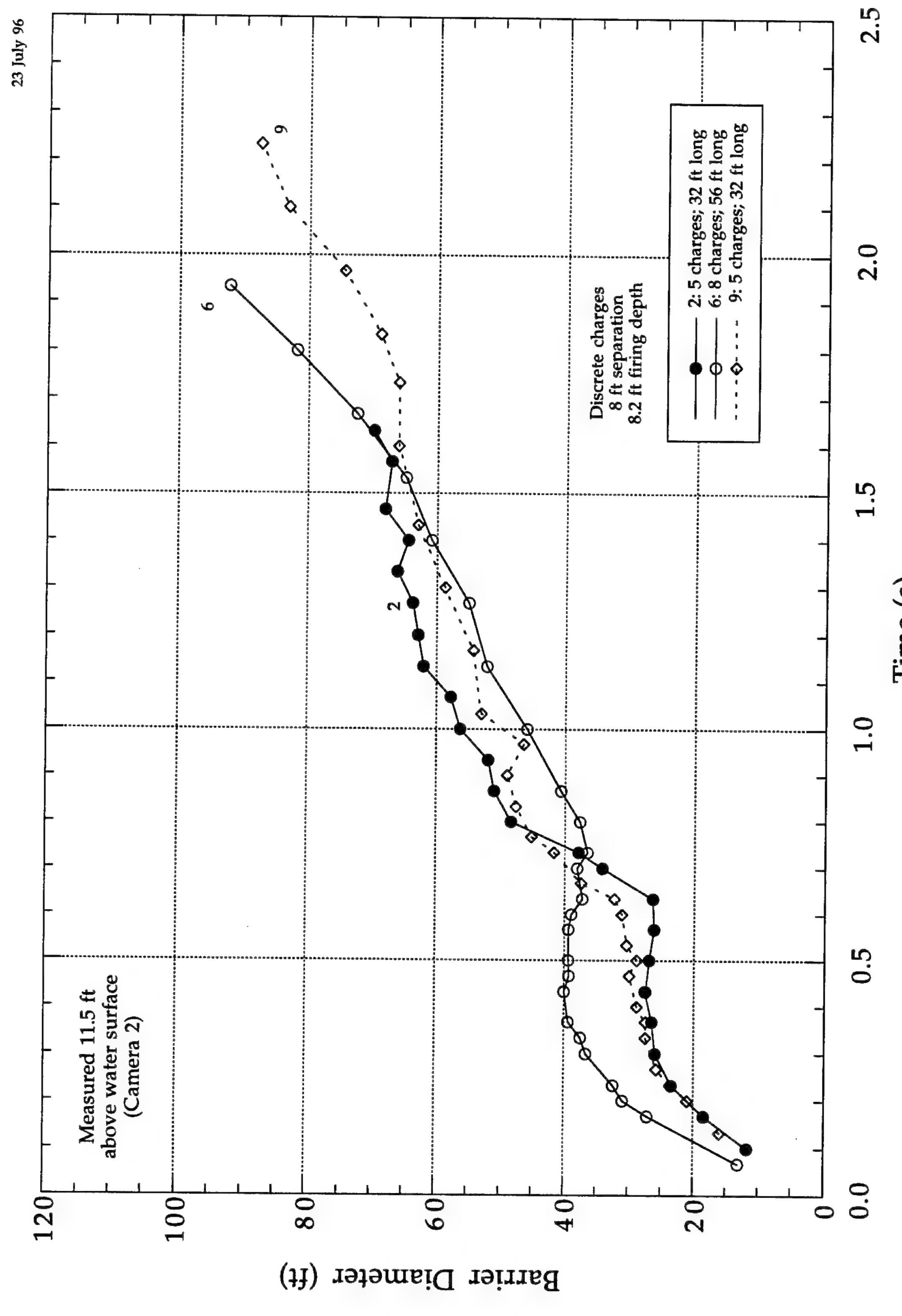

Figure 27. Barrier Diameter at 11.5-Foot Altitude: Shots 2, 6, and 9

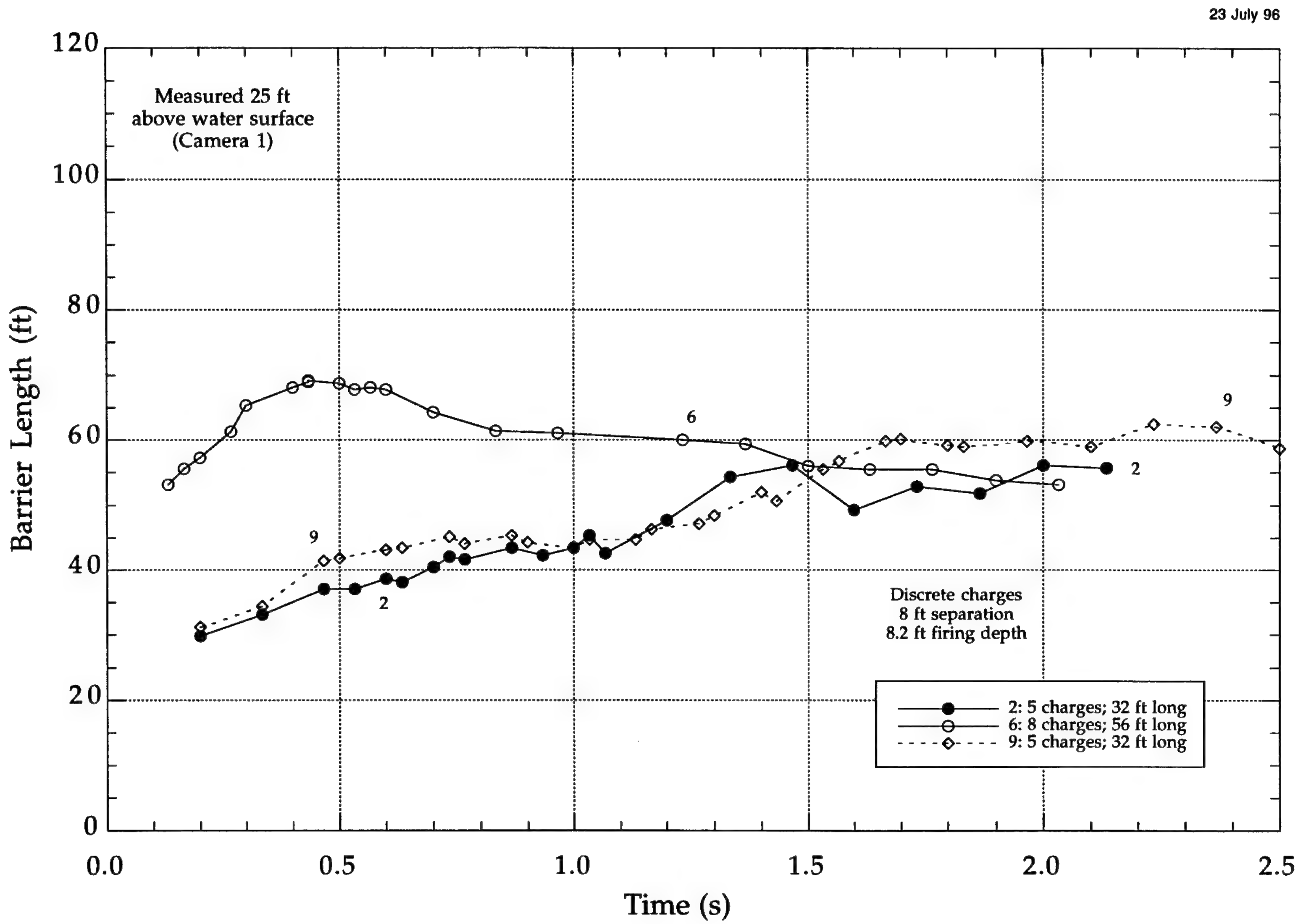

Figure 28. Barrier Length at 25-Foot Altitude: Shots 2, 6, and 9

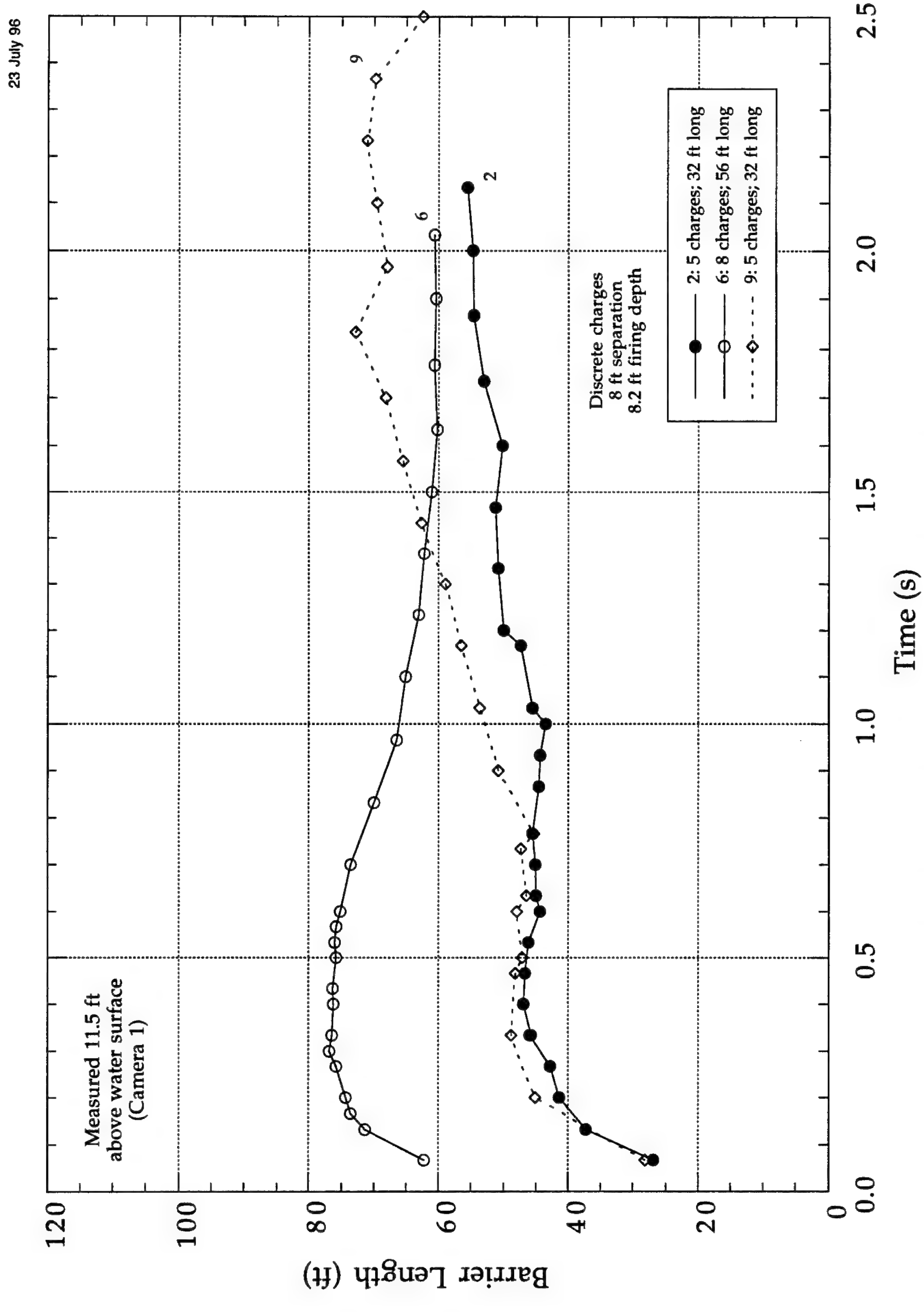

Figure 29. Barrier Length at 11.5-Foot Altitude: Shots 2, 6, and 9

The average heights of the jets on shots 2 and 9 were about the same. This is to be expected since the same charge configuration was used. Average height of the jets from shot 6 was about 10% higher over the range for which they could be distinguished from the background sky; the reason for the greater height probably has to do with coupling from the ends of the longer line charge to the center of the wall of water although this has not been established.

The diameters of the plumes above the shorter line charges (shots 2 and 9) are close enough to one another that they can be considered to be identical within the accuracy of the measurements. The plume from shot 6 (the longer line charge) has somewhat greater diameter than the other two; this, again, is probably due to a poorly understood end effect associated with a shock interaction effect at the surface associated with the greater line charge length. The rate of growth of the diameter surges when the bottom of the bubble pushes jets through the shock-induced dome; on shots 2 and 9 this occurs about 0.3 second earlier than on shot 6.

Because of the larger number of elements, and therefore the greater length of the line charge, the length of the plume produced by shot 6 is expected to be somewhat greater than that produced by the shorter charges. At both 11.5 and 25 feet above the surface, the longer charge produces a plume of greater length for the first 1 to 1.5 seconds; after 1.5 seconds the lengths of the plumes become equal as the highest water in the plume falls back to the surface. A comparison of the barrier plume dimensions for discrete line charges of differing lengths indicates a need for further study of the coupling of line charge length and surface shock interaction effects.

REPEATABILITY

Comparison of the dimensions of the plumes produced by shot 2 with the plumes produced by shot 9 and the plumes from shots 3 and 13 indicate the degree of repeatability of the phenomena for both the predicted and the constant depth line charge patterns. Shots 2 and 9 were identical shots: the number of discrete charge units as well as their depth and separation were the same. The close agreement between the dimensions of the plumes produced by the two shots was illustrated in Figures 25 through 29 and discussed in the preceding section.

Shots 3 and 13 both were discrete line charges fired in a "predicted" pattern of depths (see Table 6). Shot 13 included two more discrete charges than did shot 3. The heights of the plumes produced by these two shots are basically identical as seen in Figure 30. For this dimension, repeatability is established. Diameter surges are observed in Figures 31 and 32 at the same time on both shots, but the diameters of the shot 13 plume are slightly greater than those of the shot 3 plume. Recall that the diameter is the lateral dimension measured perpendicular to the axis of the scaled line charge.

At both altitudes - and during the first second - the lengths of the plumes from shot 13 are about 40% greater than the plume lengths from shot 3 as shown in Figures 33 and 34. This observation is not entirely unexpected since the shot 13 line charge is about 40% longer than is the shot 3 line charge. The lengths approach the same value at about 2 seconds as the water in the upper portions of the plume begins to fall back to the water surface.

Table 6. Repeatability (Figures 30 through 34)--
Dimension Data for Shots 3 and 13

Shot	Type	Depth (ft)	No. of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	lb / ft	L/D
3	Discrete	Pred	6	7 to 7.5	60	35.8	1.40	1.53
13	Discrete	Pred	8	6.75 to 7.4	80	50.3	1.39	2.10

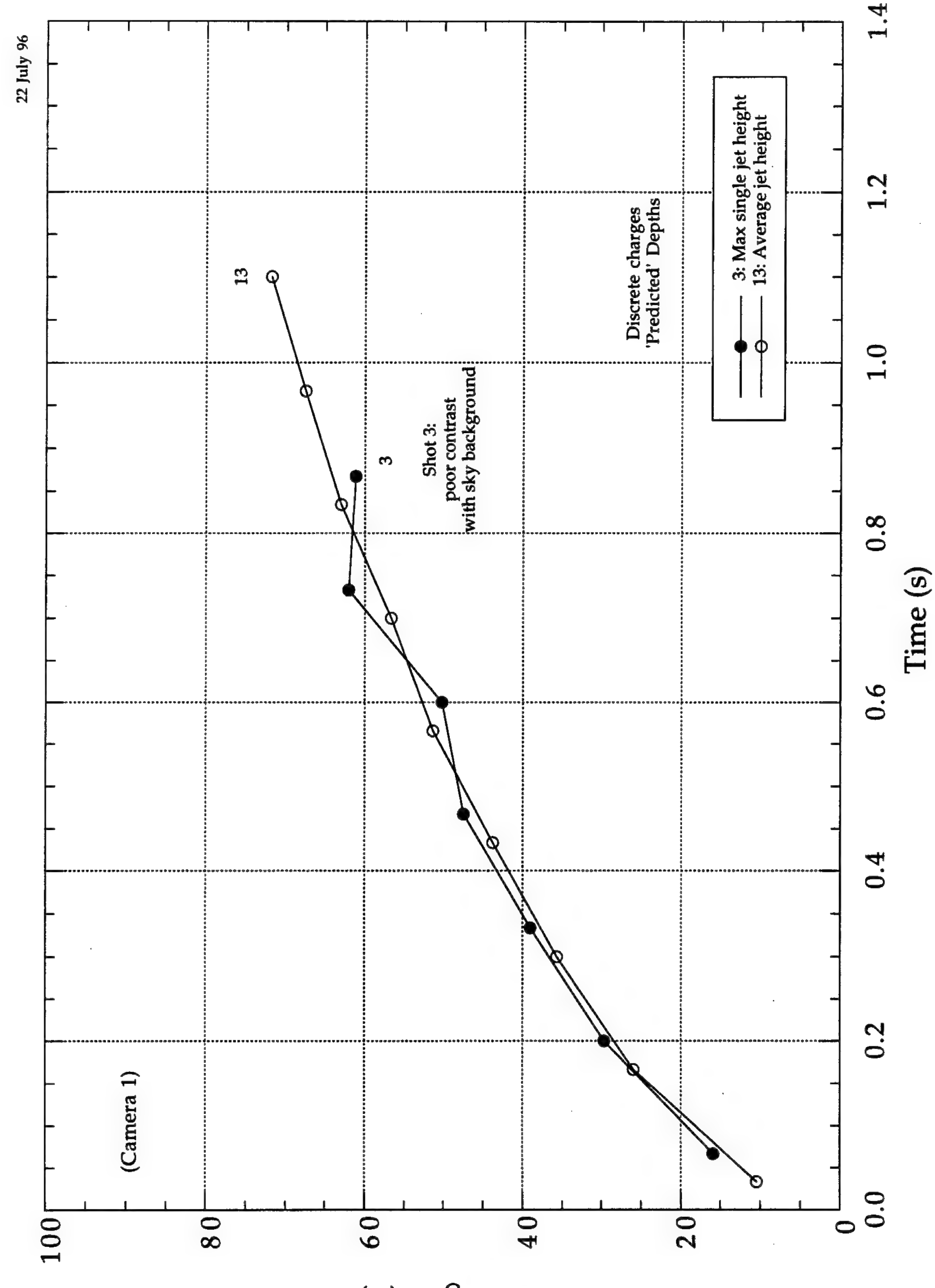

Figure 30. Barrier Height: Shots 3 and 13

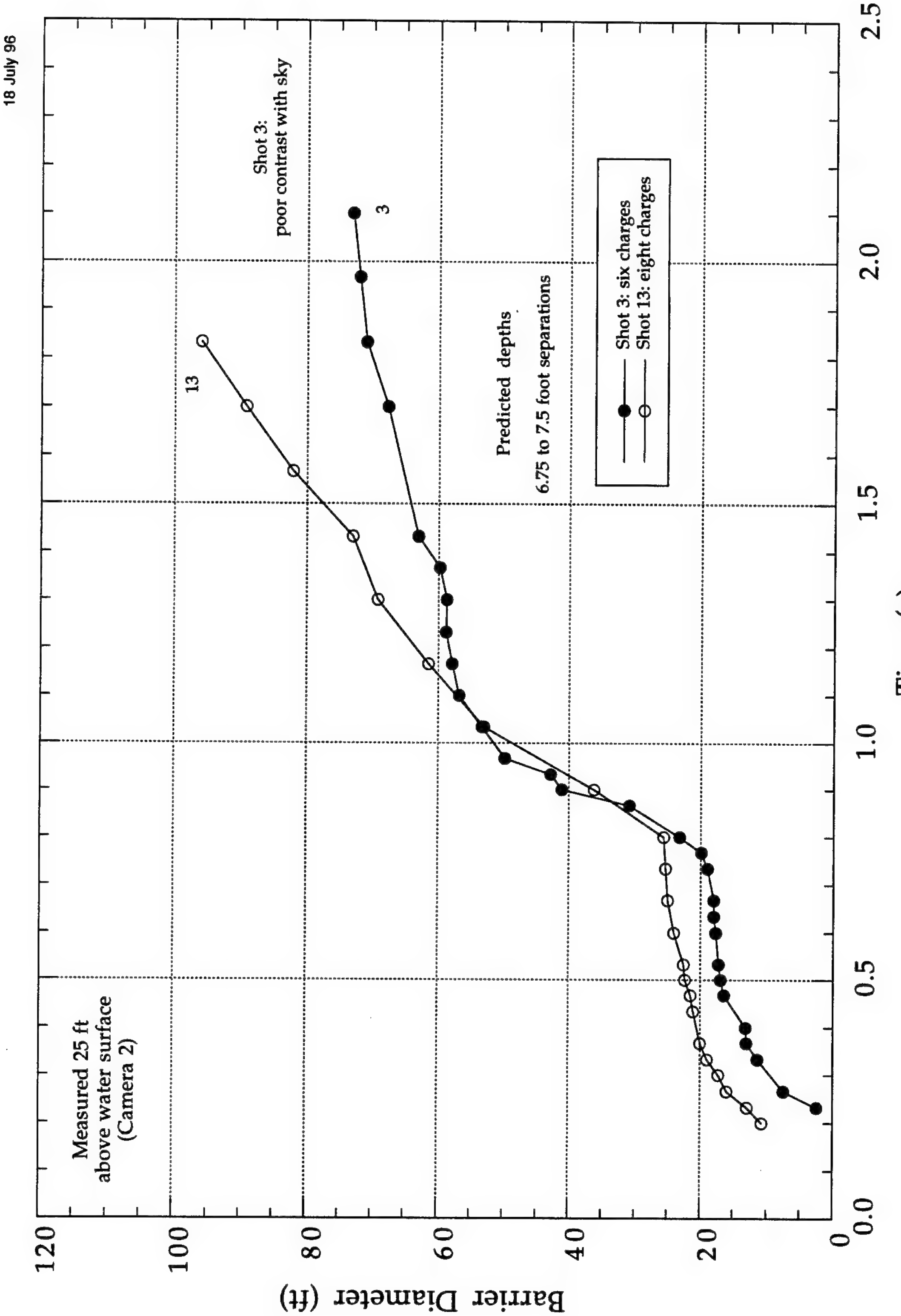

Figure 31. Barrier Diameter at 25-Foot Altitude: Shots 3 and 13

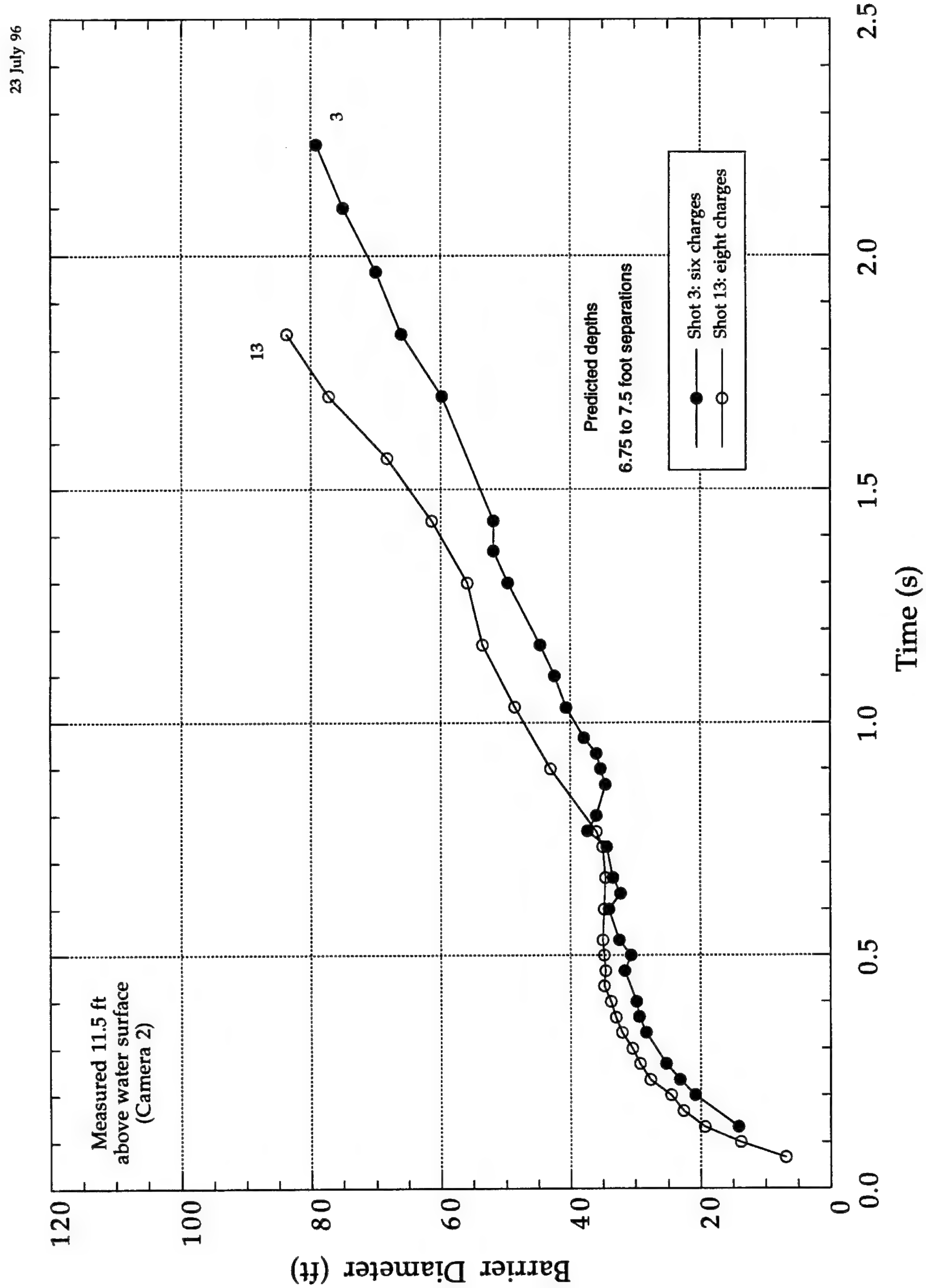

Figure 32. Barrier Diameter at 11.5-Foot Altitude: Shots 3 and 13

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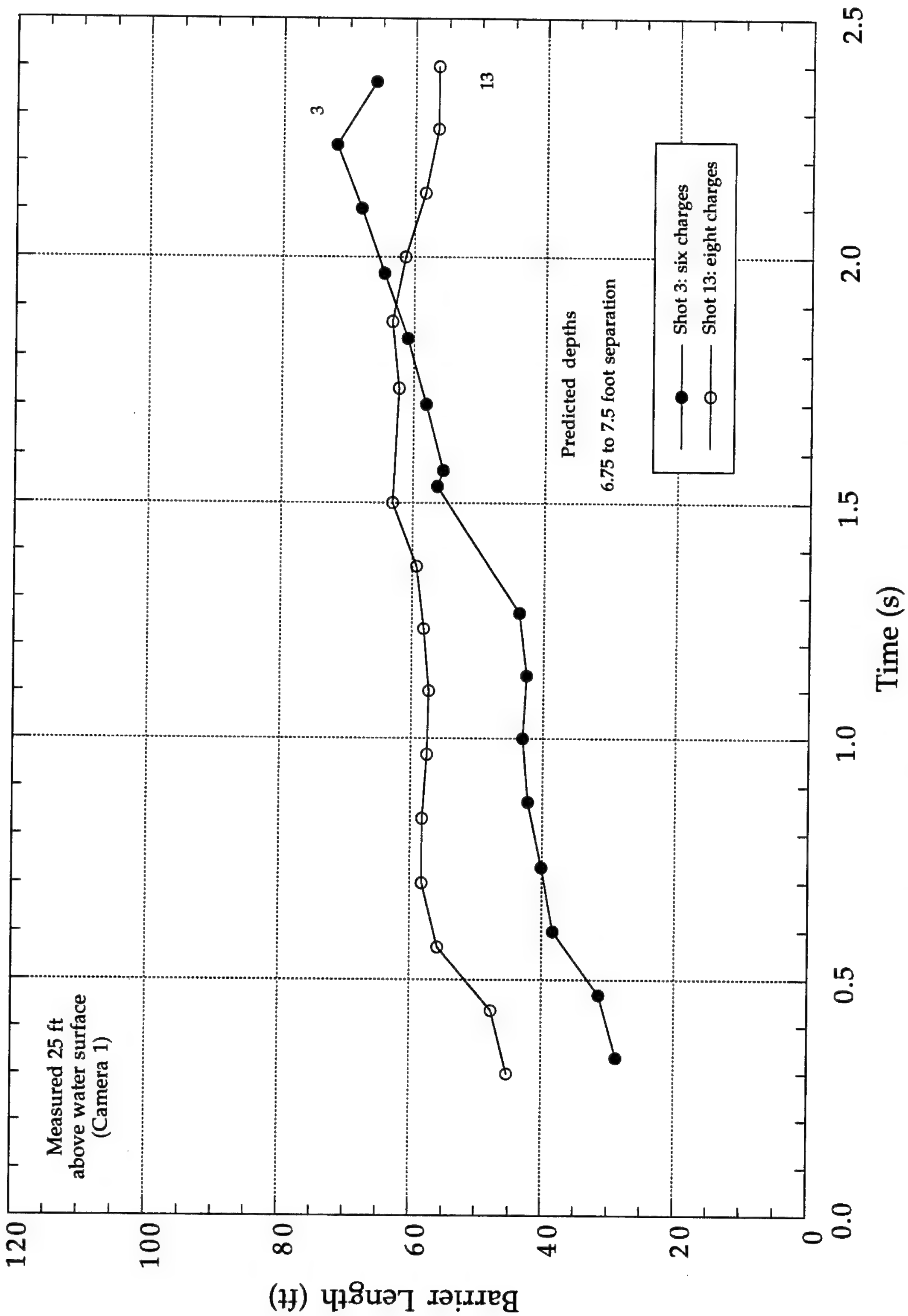

Figure 33. Barrier Length at 25-Foot Altitude: Shots 3 and 13

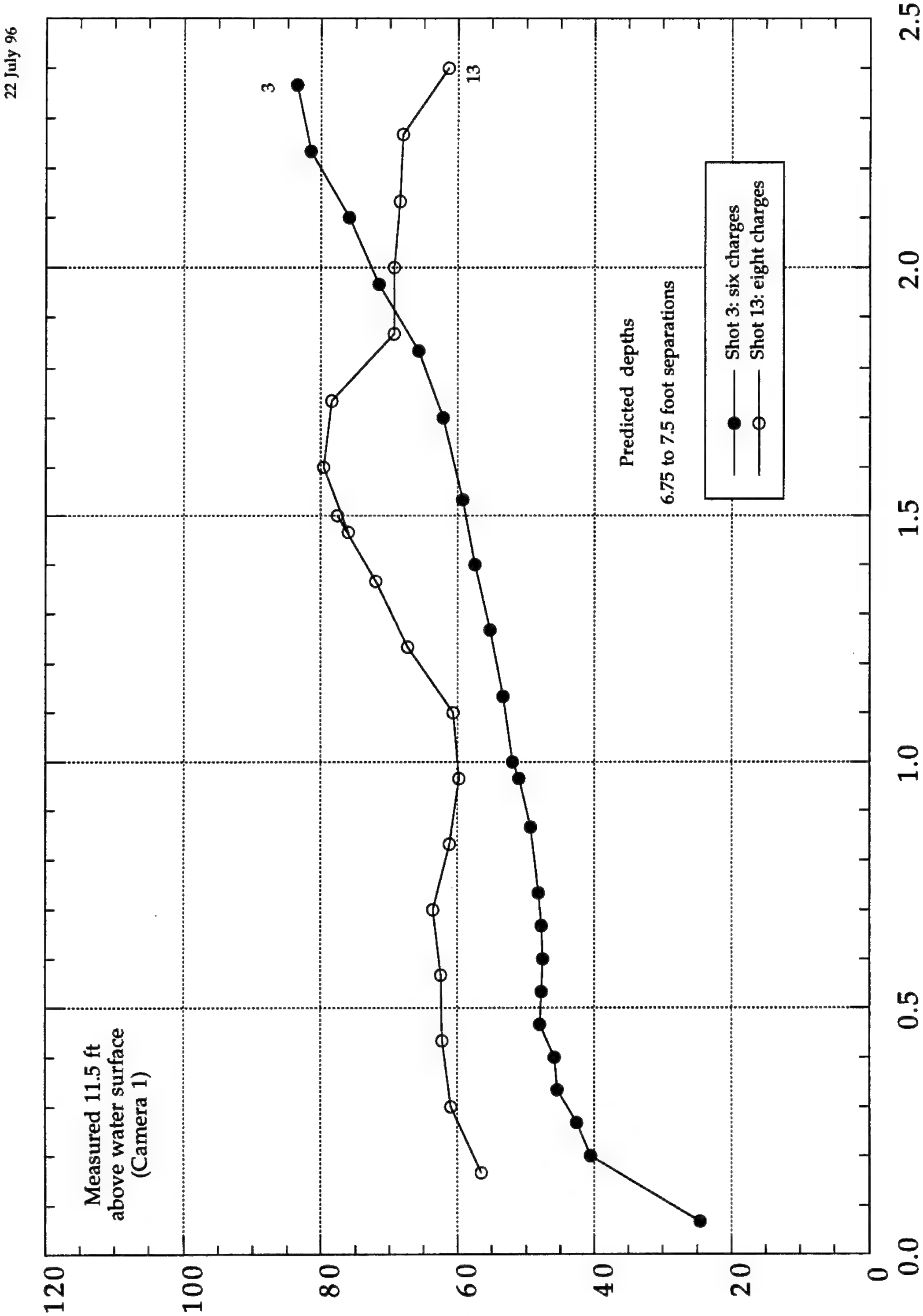

Figure 34. Barrier Length at 11.5-Foot Altitude: Shots 3 and 13

DETONATION SEQUENCE

The difference between simultaneous and sequential detonation of discrete charges is examined by comparing the height vs. time curves for charges fired in each of the two patterns. Shots 2 and 9 in the current series were fired sequentially: the detonating cord was ignited at one end and allowed to detonate each charge in sequence as the detonation in the cord arrived at each charge. Shot 3 in the series fired at the Hi Test Laboratories quarry in the summer of 1993 was fired with a detonator in each charge and the detonators all were fired simultaneously. All three shots consisted of 10-lb Composition C-4 charges placed at an 8-foot horizontal separation. The 1995 DTI shots were fired at 8.2-foot depths while the 1993 Hi Test shot was fired at an 8-foot depth (see Table 7). As seen in Figure 35, there is virtually no difference between the vertical growth rate of the plumes generated by any of these shots. Only the height of the central jet on shot 3 was determined; the only fiducial available was the average of the separations between the balloons on the surface of the pond from which the charges were suspended. The axis of the camera was neither parallel nor normal to the line of charges so that distances other than directly over the center of the charge were of dubious reliability.

Table 7. Repeatability (Figure 35)--Dimension Data for DTI Shots 2 and 9 and HTL Shot 3

Shot	Type	Depth (ft)	No. of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	lb / ft	L/D
DTI 2	Discrete	8.2	5	8	50	32.0	1.25	1.37
DTI 9	Discrete	8.2	5	8	50	32.0	1.25	1.37
HTL 3	Discrete	8	5	8	50	32.0	1.25	1.37

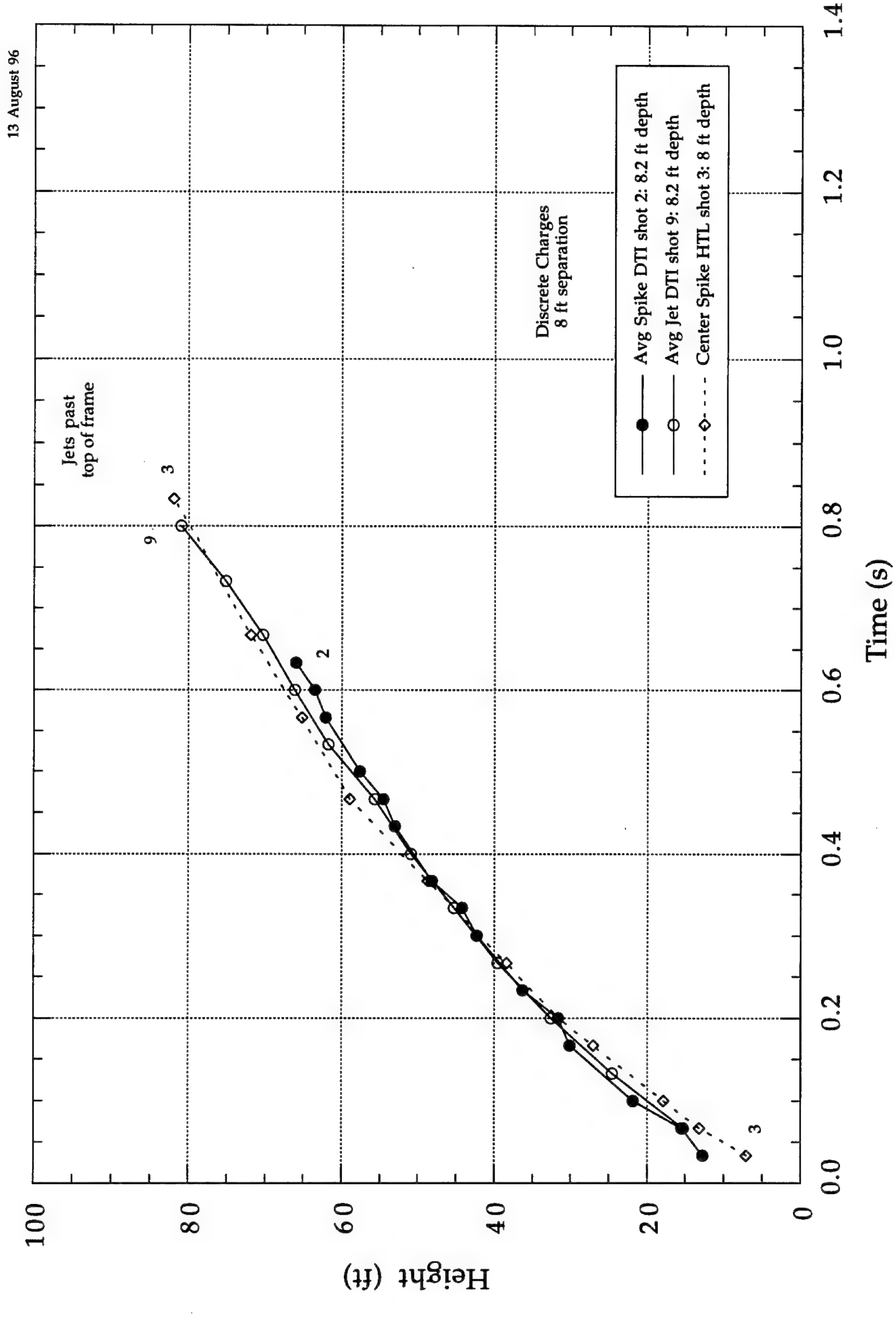

Figure 35. Barrier Height: DTI Shots 2 and 8, HTL Shot 3

SUMMARY

Thirteen underwater detonation tests were conducted in a water-filled quarry operated by Dynamic Testing, Inc., in Rustburg, Virginia. Vertical and horizontal dimensions of the surface plumes formed by the detonations were determined from scaled videotape records of ten of the tests. Limited measurements from video tapes of tests conducted in the Hi Test Laboratories quarry in 1993 were also examined. These data allowed judgments about the appropriate amount, arrangement and location of explosive material required to produce an effective defensive barrier.

RESULTS

Table 8 includes some numerical results of the measurements of the various plumes. The first three columns list the shots that were considered, the charge distribution and depth arrangement for each shot. Columns 4 and 5 list the time on each of the pertinent diameter-time plots at which a discontinuity in the curve was observed. This spurt in growth rate is associated with the bottom of the bubble pushing upward through the plumes; in the table it is headed "Plume Time."

The last four columns in Table 8 list values that are determined from a least squares fit to the height-time data for each shot. A second order polynomial of the following form was used:

$$H = H_0 + V_0 t + 0.5 A t^2$$

Time = 0 was assigned to the video tape frame in which the first whitening of the surface water is observed. H_0 is related to plume height at zero time. All the values listed in the table fall between 5 and 10 feet but are somewhat nebulous because of the half frame uncertainty in defining the time origin. V_0 is a velocity at zero time. A can be interpreted as a constant acceleration due to gravitational and viscous forces.

It was not possible to determine maximum heights attained by the plumes from the videotape images because the plume tops could not be distinguished from the sky background as their upward velocity slowed near the apogee. The uppermost points in each case were measured with less accuracy for this reason.

Maximum heights can be estimated by finding the altitude at which the derivative of the fit equation vanishes. This occurs at the time at which the plume stops rising and begins to fall back toward the surface. From the equation, this time is $-V_0/A$. (Note that A is a negative quantity.) Thus,

$$H_{max} = H_0 - V_0^2/A + 0.5\, V_0^2/A = H_0 - V_0^2/2A$$

Table 8. Numerical Characteristics of the Plumes

Shot	Charge Type	Depth (ft)	Plume Time (s) (11 ft)	Plume Time (s) (25 ft)	Height in Zero Frame (ft)	Initial Velocity (ft/s)	Constant Acceleration (ft/s^2)	Calculated Max Ht (ft)
2	Discrete	8.2	0.63	0.66	8.48	131.6	-132.0	74.1
3	Discrete	Pred	0.86	0.78	10.07	101.8	-96.6	63.7
6	Discrete	8.2	0.73	0.89	10.46	128.3	-94.5	97.6
7	Continuous	8.2	0.80	0.89	5.57	107.2	-72.6	84.7
8	Continuous	Pred	0.70	0.80	5.81	99.7	-74.7	72.3
9	Discrete	8.2	0.60	0.63	9.39	118.9	-79.1	98.8
10	Discrete	9.4	0.57	0.63	6.49	115.6	-124.2	60.3
11	Continuous	9.4	0.66	0.67	7.13	50.3	-37.0	41.3
12	Discrete	6.8	0.66	0.73	6.34	148.7	-128.1	92.6
13	Discrete	Pred	0.68	0.80	9.32	93.9	-69.2	73.1

Note: A second-order polynomial of the following form was fitted to the height-time data for each shot:

$$H = H_0 + V_0 t + 0.5\,A\,t^2$$

The maximum height was calculated from the following expression as described in the text:

$$H_{max} = H_0 - V_0^2 / 2\,A$$

Height values determined in this manner are listed in the last column of Table 8. These values should be considered to be low because of the difficulty in locating the tip of the plume against the sky; the curvature of the fit equation—and the point at which it "turns over"—is controlled largely by the precision with which the uppermost points can be located. A point should be noted about the relatively few data points of Shot 6 as shown in Figure 25. The camera zoom for Shot 6 was set at a longer focal length in comparison to the other shots. The shorter focal length that was used in the other shots provided a larger field of view so that the barrier plume was visible for a longer period of time. Figure 25 shows that the few data points of Shot 6 are higher than the comparative data points of Shots 2 and 9. Based on the video observation of Shot 6, the calculation for the maximum height is unduly influenced by the first several data points. Therefore, the calculation of the maximum plume height for Shot 6 is based on the last four points that are closely parallel but above the data points of Shots 2 and 9.

With regard to the velocities and accelerations, several points should be noted. Shot 11 is a continuous line charge, detonated at a depth of 9.4 feet, that is larger than the expected cylindrical bubble radius. Of all the shots, it has the lowest initial velocity and its deceleration is only slightly greater than the acceleration of gravity (32.2 ft/s^2). This observation indicates the importance of considering line charge arrangement and depth in designing the ultimate system.

Also note that the greatest initial velocities occur above the discrete line charges fired in the constant depth arrangement. Overall, the discrete line charge arrangements produce greater initial velocities than do the continuous line charges in the same depth arrangements.

The charge sizes used for these tests appear to be capable of producing a wall of water at least as long as the line charge. Furthermore, these charge sizes produced a plume diameter equivalent to about 10 to 15 times the depth at which the charge was fired. The maximum altitudes reached by the water plumes approached 90 to 100 feet. Many of the plumes disappeared into the sky at the top of their motion so that maximum heights were not obtained. Most were followed until their upward motion began to slow.

For the discrete line charges the diameters of the plumes approach the line charge length, resulting in a nearly circular pattern in the plane of the water surface. This occurs because the shock interaction with the cavitated surface water imparts a transverse velocity that enhances the diameter growth. The velocities are normal to the axis of the line charges (and the resulting plumes) so that they do not affect the lengths of the visible plumes.

Line charges fired at a constant depth (shot 6) were compared to those fired in a pattern simulating the depths at which the line charge will detonate after being deployed by a typical system (shot 13). The adjacent charges in shot 13 varied almost 4 ft in depth as previously indicated in Figure 8. These scaled line charge tests demonstrated that, within rather broad limits, precise control of charge depth is not a crucial issue in the design of a robust effective water barrier. The results of the 1994 field test at Aberdeen support this conclusion. Discrete 25-lb charges of PBXN-103 at varying depths successfully formed a very robust water barrier and effectively stopped 3000-ft/sec fragment simulators.

However, there appears to be a synergistic relation between the center jet growth and the length of the line charge used to produce the wall of water.

CONCLUSIONS

Underwater detonation tests of scaled line charges were successfully conducted to support the development and evaluation of the Water Barrier Ship Self-Defense Concept. The barrier plumes were generated from the single-point detonation of C-4 demolition blocks that were configured in continuous and discrete line charges. These line charge configurations successfully demonstrated water barrier plume formation using single-point detonation. This result indicates that water barrier formation and deployment can build on shallow water mine clearance systems, such as M58 and SABRE, that use line charges for a low-cost terminal defense.

The barrier plume dimensions and rise time appear to favor the discrete line charge over the continuous line charge. The discrete line charges produce underwater shock waves whose interaction with one another at the water surface projects individual jets upward at high velocity. The jets ultimately merge to form a wall of water that is higher in the early stages of plume formation than the wall of water produced by continuous line charges using the same linear charge density of explosive detonated at the same depth. The fact that discrete line charges produce a higher barrier in the early stages of plume development implies that discrete line charge plumes can become effective barriers against sea skimmers faster than continuous line charge plumes.

The microwave absorption and conductivity probe measurements that were recorded in the field test will be analyzed in another report to determine the quantity of water within the barrier plume cross section. The data generated in this report will be used to verify and refine a hydrodynamic computer model of plumes generated from the shallow detonation of underwater charges.

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